

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
N.V. PHILIPS' GLOEILAMPENFABRIEKEN

EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, HOLLAND

LAMPS FOR LIGHTHOUSES

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621.326.7 : 627.92

The conditions are discussed which must be fulfilled by a source of light intended for use in a normal lighthouse optical system. Light distribution curves are given of several electric filament lamps developed especially for use in lighthouses. The effective luminous intensity and optical range are discussed which are attained in a lighthouse optical system with different kinds of filament lamps.

Introduction

From the bonfires lighted on the shore to guide the navigator in the dark, a network of lighthouses has been developed through the years to serve as beacons in navigation. In the previous century these lighthouses were lighted with paraffin lamps and various kinds of incandescent gas burners, but in the last few decades there has been a gradual change over to electric filament lamps for this purpose. The construction of lighthouse lamps was continually improved, due to the technological advances made, until one of the most recent types contains a doubly spiralized filament for 4.2 kW.

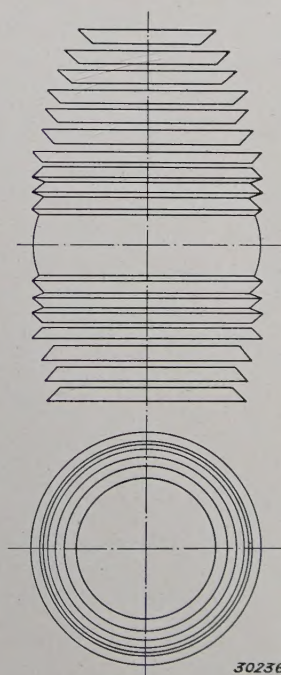
In addition to the source of light, the optical system of the lighthouse is also important, that is the combination of lenses, prisms and, in some cases, mirrors which provide for the formation of a satisfactory beam. In this article we shall first discuss the optical system in order to show what conditions must be satisfied by the source of light when it is used in combination with the ordinary lighthouse optical systems.

Formation of the beams of light

There are two kinds of lighthouse lights, stationary and revolving. In the case of a stationary light the lighthouse sends out its light uniformly distributed in all directions in a horizontal plane, so that the whole horizon is always uniformly illuminated. If all lighthouses were provided with such a stationary light it would be difficult to distinguish one from the other. By having large lighthouses which send out only a few, slightly divergent beams, while the whole optical system revolves slowly, the observer at any point on the hori-

zon will observe flashes of light at regular intervals. Each light may be given an individual character by making the length of the successive intervals different for each lighthouse. Moreover because of the concentration of the light in a few narrow beams a much greater optical range of the light is obtained.

In order to form the beams, emitted by a lighthouse, use is made of lenses and prisms which are combined in a special way and make up the optical system of the lighthouse. For a stationary light an optical system is necessary which is rotationally



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Fig. 1. Barrel-shaped optical system for a stationary light.

symmetrical around a vertical axis (see the barrel-shaped system shown in *fig. 1*). The main cross section through this lens is shown in *fig. 2*. The cylindrical echelon lens (*MN*), of which

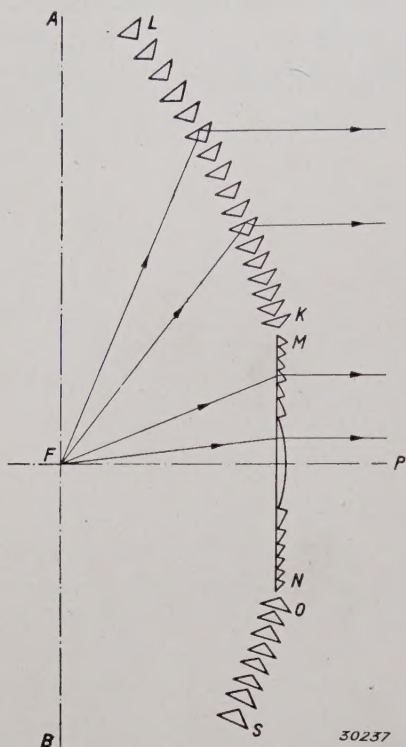


Fig. 2. Cross section of a lighthouse optical system. *F* is the focus, *MN* an echelon lens. *KL* and *OS* are prismatic rings. *AB* is the vertical through the focus.

the vertical line *AB* through the focus *F* is the axis of revolution, consists of a middle section with several ring-shaped sections of lens arranged in steps at the top and bottom; all the rays which pass through this lens from the focus are refracted in such a way that they leave the lens in a horizontal direction. The lens *MN* is flanked at the top (*KL*) and bottom (*OS*) by a number of prismatic rings with *AB* as axis, at the rear surface of which the rays of light are totally reflected, and which are arranged in such a way that the rays from *F* leave the optical system in a horizontal direction.

A revolving optical system consists of several panels each of which provides for the formation of one beam. Such an optical panel can be obtained by causing the cross section in *fig. 2* to rotate around *FP* as an axis. The panel shown in *fig. 3* is then obtained, and is composed of a Fresnel lens surrounded by a number of prismatic rings with *FP* as an axis. The different parts of this optical system are so arranged that all the rays from the focus leave the system parallel to the main axis. If a number of such panels are joined side by side with a common focus around the axis of rotation *AB*, the

light emitted by the source in all directions is used effectively to make up the beams of the lighthouse except for a very small part which is lost.

The beam of light formed by such an optical panel is composed of two different parts:

- 1) the part formed by the lens, and
- 2) the part contributed by the prismatic rings.

The form and position of the source of light affect these two components in quite different ways. If standing immediately in front of the panel one observes the source through a small hole in a screen, so that only a small portion of the surface of the lens contributes to the beam, the source of light may plainly be seen in an upright position through every element of surface of the Fresnel lens. The images which are seen through different surface elements of the lens differ only slightly.

If, however, a surface element of one of the prismatic rings is observed the image of the light source seen depends very much upon the position of the element of surface chosen. If only elements of surface in the neighbourhood of the horizontal bisector of the panel contribute to the formation of the beam the light source is seen upright, surface elements in the neighbourhood of the vertical bisector of the panel give an inverted image, while through surface elements at 45° to one of the former directions the light source is seen lying on one side or the other, thus turned through an angle of 90° .

Since the surface elements of the prismatic rings

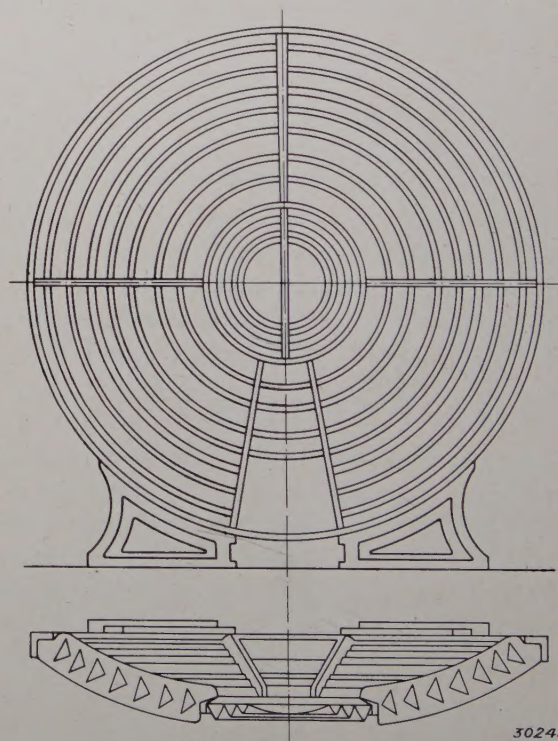


Fig. 3. An optical panel obtained by allowing the cross section in *fig. 2* to rotate around *FP* as axis.

lie so far outside the main axis, one looks through them at the light source in a direction which makes a fairly large angle with the main axis. A certain amount is also contributed to the total light beam given by the prismatic rings by very different projection figures of the source. Although the light source is not an uninterrupted surface of uniform brightness the light intensity of the total beam sent out by the optical system does not change very much over the core of a perpendicular cross section, since we are concerned with the sum of the contributions of all these different component beams.

In the case of lighthouse lights, a beam is considered homogeneous if the light intensity curve in a plane through the axis of the beam is a trapezium, so that the light intensity is constant throughout the core of the beam. It is customary to call the angle of divergence within which the light intensity does not vary, the spreading of the beam.

The beams of lighthouses should be as homogeneous as possible. The ideal would be to have a sphere of constant brightness as source, but with suitable forms of light source the above-described optical systems can give a fair approximation of a homogeneous beam of light. The spreading of a beam which is emitted from the whole panel is determined by the spreading of the outermost prismatic rings, and depends further upon the shape of the light source. In constructing a light source for a lighthouse therefore the requirements must be taken into account which will be made as to homogeneity and spreading of the beam.

Brightness of the source of light

If we assume that the light source is situated at the focus of a lens, or of a mirror in some cases, the light intensity of the beam emitted through this optical system is proportional not only to the solid angle of divergence of the system but also to the average brightness¹⁾ of the source of light. In order to increase the intensity of the beam, attempts have been made not only to increase the surface of the lens but also the brightness of the sources of light. Since the brightness of light sources has been so much increased in recent years, it has become possible to obtain satisfactory light from lighthouses without very large and therefore very expensive panels.

The brightness of the paraffin lamps with six wicks was only about 10 c.p./sq.cm, that of in-

candescent paraffin burners was already about 40 c.p./sq.cm.

In addition to these sources of light electric arcs are also used in lighthouses, but they have practical disadvantages in spite of the fact that they may attain very high brightnesses of up to 10^5 c.p./sq. cm in the case of the high-intensity arc. A very important objection to the use of electric arcs in lighthouse optical systems is the fact that the arc does not occupy a stationary position on the electrode, so that the centre of the light source is not always situated with sufficient accuracy at the focus of the optical system, with the result that the correct formation of the beams is very much disturbed. Now that electric filament lamps specially developed for lighthouses are available, which do not need constant supervision, it is naturally considered to be a great objection that electric arcs must be constantly supervised. In the lighthouse at Creach d'Ouessant on the west coast of Brittany, constructed by the firm of Barbier Benard and Turenne of Paris, and shown in *fig. 4* extremely intense arc lamps have never-

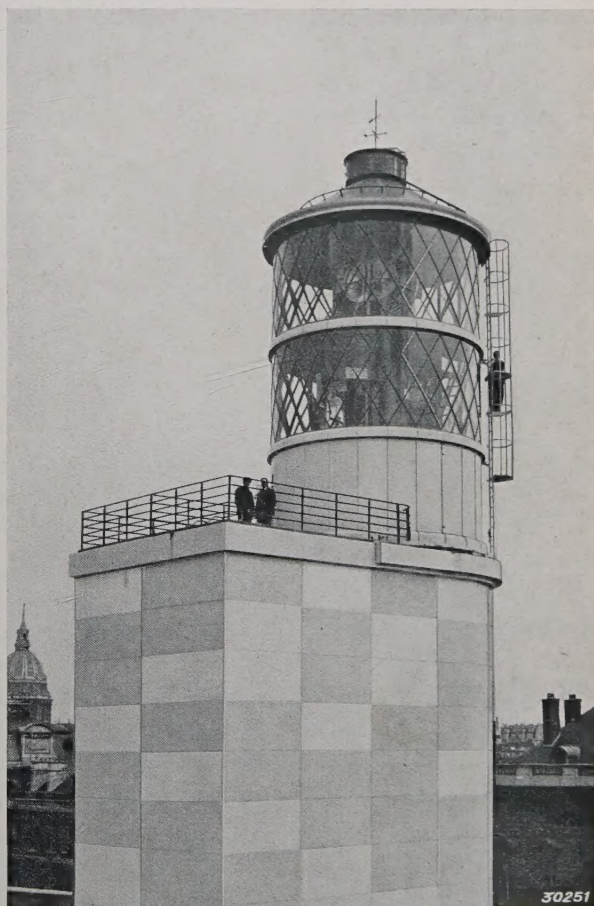


Fig. 4. The upper part of the lighthouse constructed by the firm of Barbier, Benard and Turenne of Paris at Creach d'Ouessant on the west coast of Brittany.

¹⁾ By average brightness is meant the light intensity of the light source measured in the direction of the axis of the beam, divided by the area of the cross section perpendicular to this direction.

theless been installed for very bad weather conditions. These lamps, however, are so very expensive in use that in more favourable weather they are replaced by considerably cheaper electric filament lamps for 110 volts, 3 000 W.

The water-cooled super high pressure mercury lamps have a high surface brightness (for instance $3 \cdot 10^4$ c.p./sq. cm) which approaches that of the high-intensity arc, without the disadvantage of mobility of the centre of the light source possessed by the crater of the electric arc. Nevertheless this water-cooled mercury lamp cannot immediately be installed in the existing lighthouse optical systems, because it is so slender and linear in form and must in addition burn in a horizontal position. It may perhaps be found possible to use the super high pressure mercury lamp as a light source in lighthouses by using several mercury lamps together or by combining several optical systems.

From its foundation in 1909 the Testing Station of the Netherlands Lighthouse Service has always tried to adapt new light sources with higher surface intensities for use in existing lighthouse optical systems²⁾. The incandescent paraffin burners were improved with this purpose in view, and attempts were also made to construct suitable light sources out of Nernst rods. After the appearance of the gas-filled electric lamp with a spiralized filament, these lamps were adapted for use in lighthouses, in collaboration with Philips. The problem was here to construct a filament system whose projections in different directions have as nearly as possible an equally large radiating surface which forms a well-connected whole, while the focus lies in the centre. This could for example be approximated by similar filaments mounted in three mutually perpendicular planes, but since this could not be carried out technically, the filaments were hung in only two vertical planes perpendicular to each other and the third horizontal plane was omitted.

A lamp with such a "cross-shaped" filament system was first constructed in 1918 for 108 volts, 20 A. Since at that time some difficulty was experienced with sagging of the filament, the filament system had to be made 2.5 times as wide as its height. With these first electric filament lamps for lighthouses an average brightness of 450 c.p./sq. cm was already obtained, which meant almost a ten-fold improvement over the ordinary Pharoline incandescent lights of those days, which had a brightness of about 50 c.p./sq. cm. In the further

development of these lamps with cross-shaped filament system two standard types have been evolved, namely for 80 volts, 30 A, and for 80 volts, 50 A. Since these 4 kW lamps have proved their usefulness especially in the well-known Brandaris lighthouse at Westerschelling which is shown in *fig. 5*, they are often called Brandaris lamps.

When the difficulties connected with the sagging of the filaments had been overcome, cylindrical filament systems could be made for lighthouse lamps, whose projections in different directions more nearly approached the ideal of continuous incandescent surfaces of the same size and brightness. The surface brightness was further increased during the course of years by increasing the temperature of the filaments. Since in the course of years also a method of treating tungsten wires was learned by which better recrystallization is obtained, the most modern lighthouse lamps are now fitted with doubly spiralized filaments.

Filament systems

The filament systems now in use may be divided into three main classes (*fig. 6*) namely:

A Cone-shaped filament systems of singly spiralized wire, all parts of which are connected in series.



Fig. 5. The lighthouse Brandaris at Westerschelling.

²⁾ Cf. No. 1 of the literature.

B Cylindrical filament systems of singly spiralized wire which may consist of one (*B1*) or more (*B2* and *B3*) circuits.

C Doubly spiralized filament systems.

In the following we shall deal with systems *B* and *C*. If the cylindrical filament system is divided into two equal current circuits (*B2*), these circuits may be connected in series as well as in parallel. A lamp for 100 volts, 60 A may therefore burn on 100 volts with 60 A as well as on 200 volts with 30 A. If the two parts are connected in parallel, then as a rule when one of them is defective the other continues to burn. Since it is important to keep points with a large potential difference as far away from each other as possible, the lamps are connected according to the scheme indicated in *fig. 7*. The opposite end-points *M* of the two windings are always connected to each other and led out together, while the other two end-points are connected separately to *P* and *Q*. A direct or alternating voltage of 200 volts is applied between

P and *Q*, so that *M* automatically reaches a potential which is half of that between the ends. A direct or alternating voltage of 100 volts is, however, applied between *M* and the points *P* and *Q* which

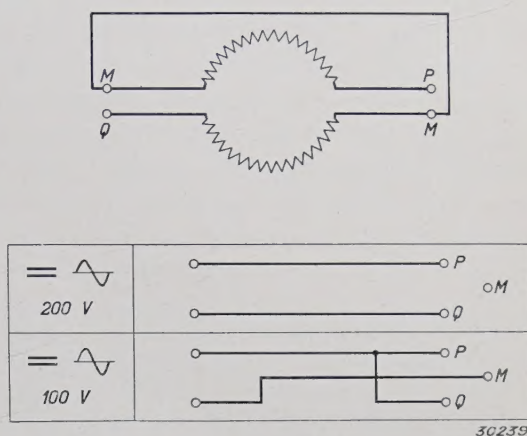


Fig. 7. Circuit diagram for a lighthouse lamp consisting of two current circuits. The lamp can be connected to direct or alternating voltage of 200 or 100 volts.

are then connected to each other. Between two points of the filament lying close together there is therefore never a greater potential difference than 100 volts.

Especially for high power consumption it is very important to use a lighthouse lamp which exerts an equal load on the three phases of the ordinary three-phase mains. Therefore, for powers of 1500, 3000, 6000 and 10000 W, lamps have been developed with filament systems divided into three equal parts (*fig. 6, B3*). Such a lamp is shown in *fig. 8*. A similar lamp for 110 volts 3 kW is used in favourable weather in the lighthouse on the westcoast of Brittany shown in *fig. 4*. From the circuit diagram of *fig. 9* it may be seen that these three-phase lamps can be connected to a direct and alternating voltage as well as to a star connection of 110 volts. For lighthouses which must often be supplied with current from a very distant source, these three-phase lamps also mean a saving in the cost of the supply lines since they are more evenly loaded than when a lamp with two current circuits is connected to a three-phase network.

Doubly spiralized filaments (*fig. 6C*) are now used in lighthouse lamps (*fig. 10*) for 70 volts, 60 A as well as for 60 volts, 50 A.

In *fig. 11* the polar luminous intensity diagram is given for this lamp for 3 kW, while for comparison *fig. 12* shows the same diagram for a lighthouse lamp with a cylindrical filament system for 60 volts, 50 A. It may be seen clearly from these figures that with the doubly spiralized filament, while higher intensities of light are obtained, the intensity is less

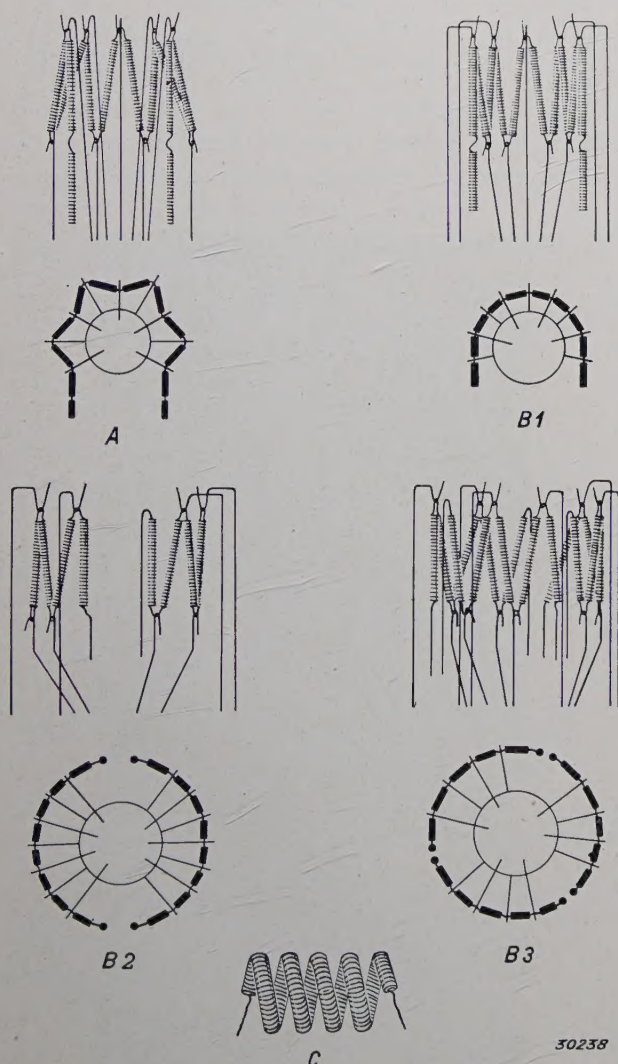


Fig. 6. Filament systems. *A* conical, *B* cylindrical, consisting respectively of 1, 2 or 3 current circuits. *C* doubly spiralized.

evenly distributed over the whole circumference than in the case of the cylindrical system. Fig. 13 shows the doubly spiralized filament seen from different angles in the horizontal plane³⁾. With each photograph the angle of observation is given in degrees⁴⁾ (cf. fig. 11), the luminous intensity in candle power, the projected surface in square centimetres and the average brightness in c.p./sq. cm. Since experience has shown that better results are obtained in lighthouses with doubly spiralized filaments than with other lamps having the same or even somewhat greater power, we shall deal with this point in more detail in the following.

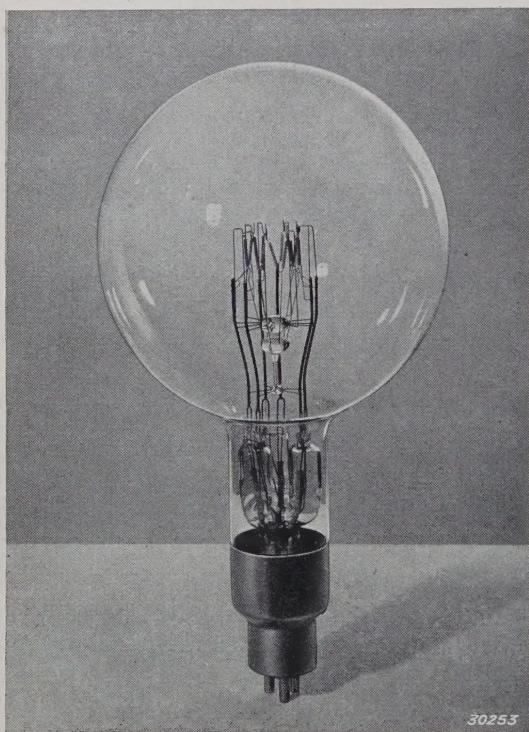


Fig. 8. Lighthouse lamp consisting of three current circuits in order to load the three-phase mains symmetrically.

Comparative measurements on lamps with different filament systems⁴⁾.

The Testing Station of the Netherlands Lighthouse Service has carried out measurements on five lamps with different filament systems, namely: 1 lamp with a cross-shaped filament system, 2 lamps with a cylindrical filament system and 2 lamps with doubly-spiralized filaments.

These lamps were placed one after another at the focus of an optical panel and the distribution of the light in the beam emitted was measured. The dimen-

sions and other data of these lamps are given in the following table together with the maximum, luminous intensities of the beams.

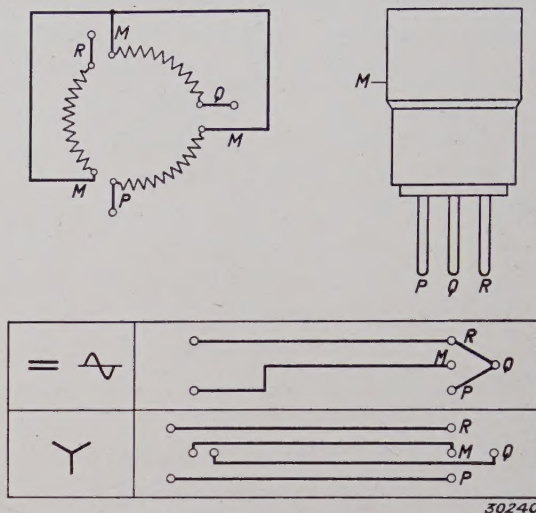


Fig. 9. Circuit diagram for a lighthouse lamp with three circuits which can be fed with direct or alternating voltage, but which is especially constructed to produce a symmetrical loading of three-phase mains in star connection.

Effective luminous intensity of a lighthouse

By the effective luminous intensity of a lighthouse with a rotating optical system, sometimes called the light value, is understood the intensity of a

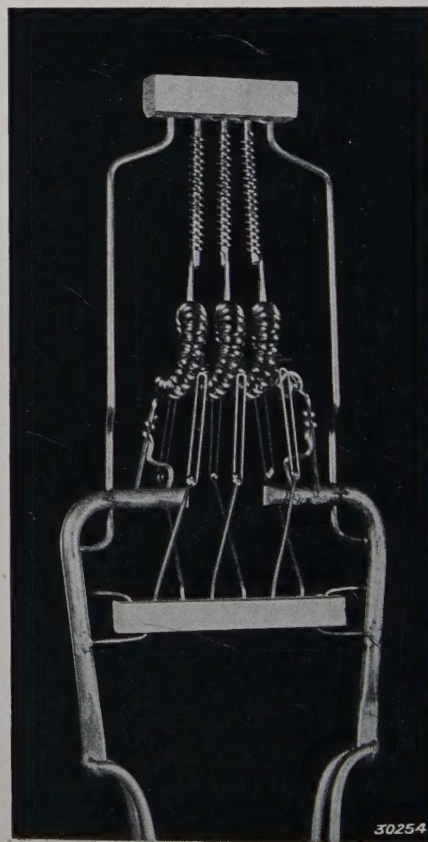


Fig. 10. Doubly spiralized filament for a lighthouse lamp.

³⁾ Cf. Nos. 4 and 5 of the literature.

⁴⁾ Although somewhat different values are valid for the lighthouse lamps now being manufactured, the original data are given here since they give a sufficiently correct impression.

stationary light which can be observed from an equally great distance.

As is known, the light impression received from a source of light does not depend exclusively upon

of the order of magnitude of 0.1 sec. which must be determined experimentally.

Formula (1) only holds strictly at the limit of visibility, i.e. in the neighbourhood of the thresh-

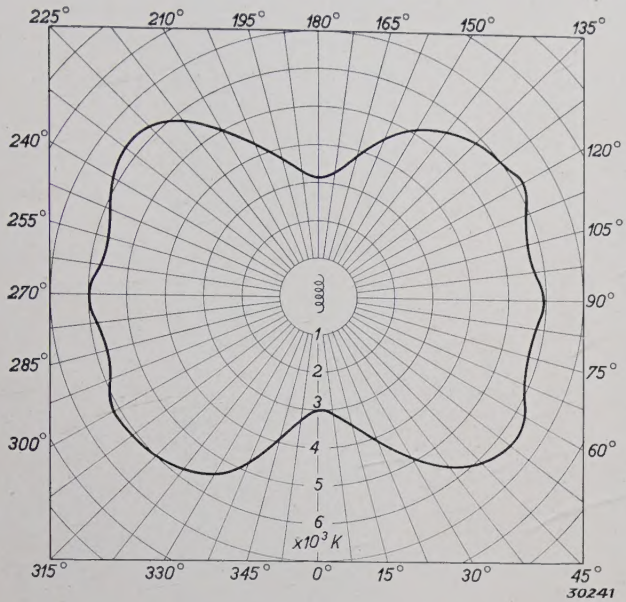


Fig. 11. Polar diagram of light intensity, measured in the horizontal plane, of a lighthouse lamp with a doubly spirialized filament for 60 volts, 50 A.

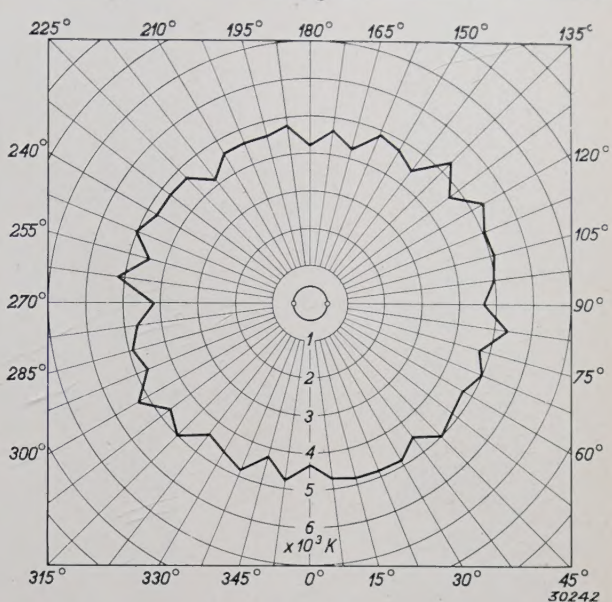


Fig. 12. Polar diagram of light intensity, measured in the horizontal plane, of a lighthouse lamp with a cylindrical filament system for 60 volts, 50 A.

the intensity of the light, but also upon the time during which the impression lasts. It used to be believed that a flash of light lasting 0.1 sec gave the same light impression as a fixed light of the same intensity, but it was found later that this is only true when the flashes of light last longer than 1 sec. Blondel⁵⁾ and Rey have shown that, for the case where the luminous intensity I is constant, as long as the light is present, the effective luminous intensity I_e can be determined by the formula

$$I_e = \frac{I t}{c + t} \dots \dots \dots (1)$$

where t is the duration of one flash and c is a constant

hold value of the light impression. As the threshold value of the intensity of illumination presented by a point source of light to the eye the value $2 \cdot 10^{-7}$ lux is internationally established; this is by no means an extreme value but a value which may confidently be used under the most unfavourable conditions in the dark. Under favourable conditions the actual threshold value may amount to only one-twentieth of this value!

It is not easy to determine accurately the value of the constant c . In practice, however, very usable results are obtained, when, for lighthouses with a trapezium-shaped light distribution, formula (1) is used with $c = 0.15$, and t is taken as the total duration of the flash and I the maximum luminous

⁵⁾ Cf. No. 6 of the literature.

Lamp No.	Filament system	Width	Height	Voltage	Power	Light	Brightness	Maximum candle power of beam
	—	mm	mm	volts	watts	lumens	c.p./sq.cm.	10 ⁶ c.p.
1	cross-shaped	28.0	28.0	80	3 892	67 300	865	2.3
2	cylindrical *)	23.4	23.0	110	3 770	69 000	1 280	2.46
3	cylindrical *)	22.5	24.0	60	2 961	49 800	920	1.56
4	doubly-spiralized	23.5	21.2	70	4 200	84 100	1 680	4
5	doubly-spiralized	19.5	17.2	60	2 907	59 900	1 720	3.5

*) Lighthouse lamps have since been constructed with cylindrical filament systems with a power of 4 and 3 kW respectively and a light flux of 78 000 and 54 000 lumens respectively, which have a brightness of 1400 and 1030 c.p./sq.cm, and which in use may be expected to give a somewhat higher intensity of the beam when used in the same optical system as the cylindrical filament systems mentioned in this table.

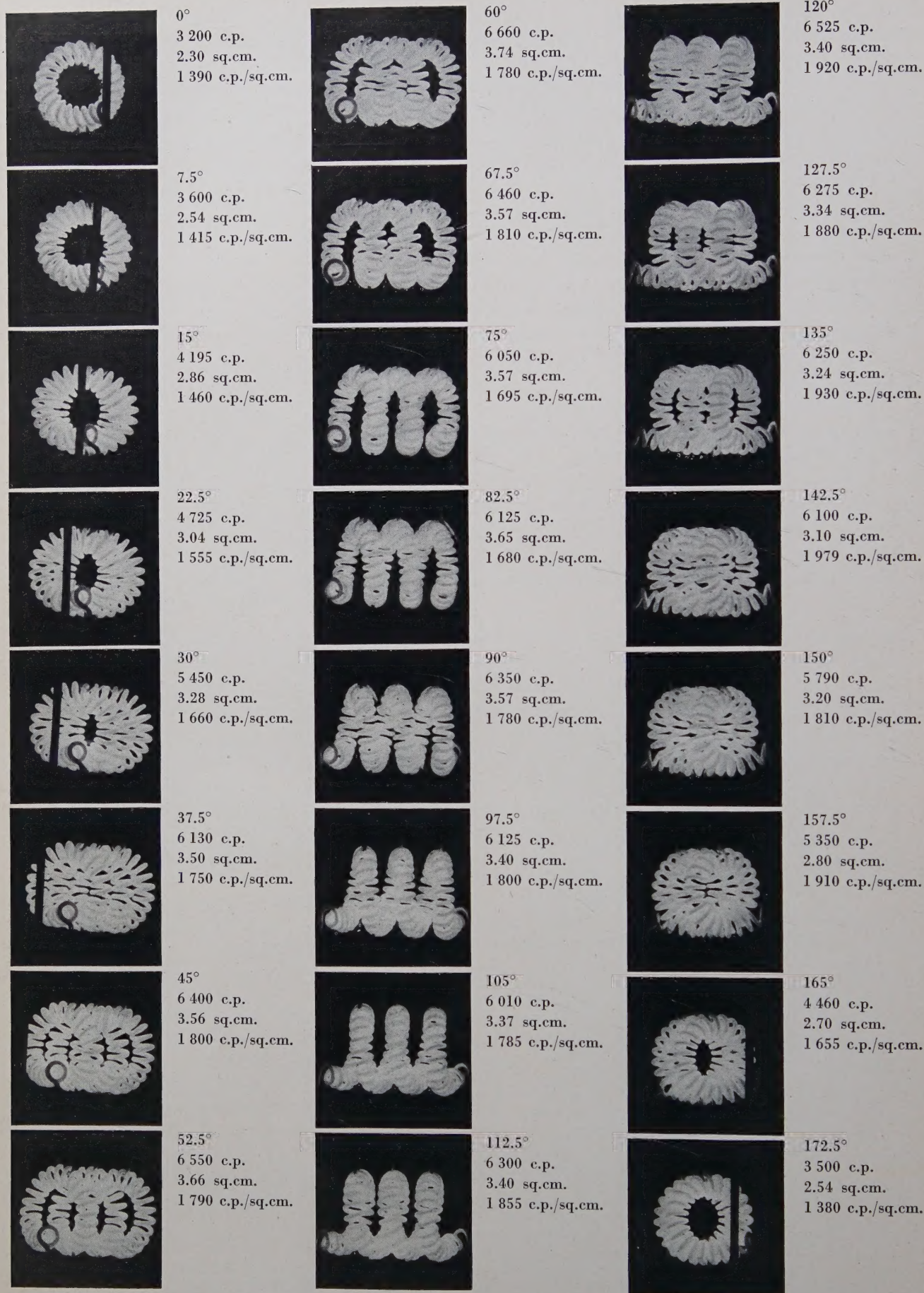


Fig. 13. Doubly spiralized filament seen from different angles in the horizontal plane (cf. fig. 11). With each picture the angle is indicated at which the picture is taken, the candle power, the projected surface in sq. cm and the average brightness in c.p./sq.cm.

intensity I_m which occurs at the core of the beam. Although the third International Lighthouse Conference in Berlin did not accept formula (1), it is nevertheless used on a large scale, since the results have been found reliable. We shall therefore continue to use formula (1) in this article.

If d represents the diameter of the incandescent body and f the focal length of the optical system, and therefore also the distance between source and optical panel, the small angle within which the optical panel transmits light is equal to d/f radians. If the whole optical system makes n revolutions per minute, the duration of a flash is given by

$$t = \frac{d/f}{2 \pi n} 60 \text{ sec.} \dots (2)$$

When a maximum light intensity I_m has been determined in the laboratory, then in normal use it must be taken into account that about 15 per cent of the intensity may be lost by blackening of the lamp and possible burning at too low a voltage, while about 10 per cent is absorbed by the framework of the lighthouse windows and 10 per cent more by all the glass. A total factor of 0.7 is calculated for this weakening⁶⁾. For the effective luminous intensity we therefore finally obtain the formula:

$$I_e = 0.7 \frac{t}{0.15 + t} I_m \dots (3)$$

Since for this determination of the effective luminous intensity I_e use must be made of somewhat uncertain factors, a maximum luminous intensity, $0.7 \cdot I_m$, is given, taking into account the absorption, which maximum is however always much higher than I_e . For a constant effective luminous intensity $I_e = 1.5 \cdot 10^6$ c.p. it is shown in fig. 14 how the maximum intensity varies with the duration t of the flash⁷⁾, when c is taken equal to 0.15. For large values of t , $0.7 \cdot I_m$ is found to approach I_e as an asymptote. For durations of more than 1.4 sec the light intensity $0.7 \cdot I_m$ of a rotating light is found to be less than 10 per cent higher than its effective light intensity I_e .

The maximum light intensity of the beam is proportional to the brightness of the source, which can be represented by the quotient of the intensity i of the source and its projected surface S . This latter is proportional to the square of the diameter d of the source. Since the flash time t is proportional to this diameter, the effective intensity I_e is found

to be proportional to the product of i/d^2 times $d/c'+d$ so that I_e is proportional to

$$\frac{i}{d^2} \cdot \frac{d}{c' + d} = \frac{i}{d(c' + d)} \dots (4)$$

It is therefore possible to increase the effective intensity of a lighthouse lamp with the same intensity of the source by making the filament system as concentrated as possible. If care is taken that $i/d(c' + d)$ remains constant, lighthouse lamps can be constructed which, in the same optical system, have the same effective intensity as higher powered lamps with a less concentrated filament system. On the basis of these considerations it could be expected that especially in lighthouse lamps the application of doubly spiralized filaments with their great brightness and small projection image would meet with much success.

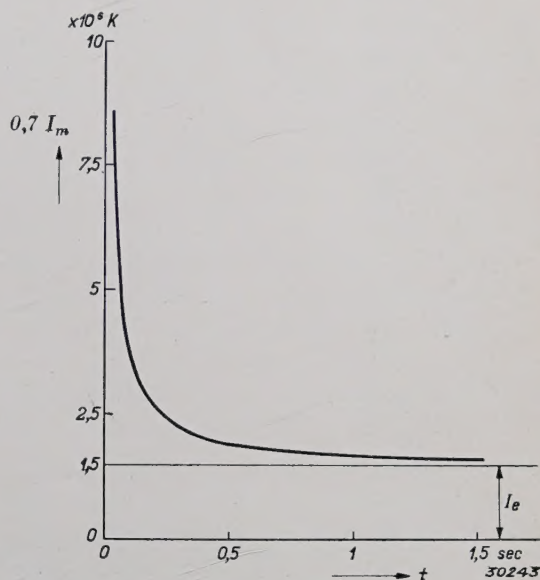


Fig. 14. The maximum light intensity $0.7 I_m$ in c.p. as a function of the duration of a flash t in sec, necessary to obtain an effective light intensity $I_e = 1.5 \cdot 10^6$. This relation is represented by formula (3).

Optical range of a lighthouse

For a navigator it is very important to know at what point a given lighthouse must come into his field of vision. This of course depends not only upon the effective light intensity I_e of the lighthouse, but also, among other factors, on the coefficient of transparency a of the air, i.e. the fraction of the light which is transmitted through unit distance⁸⁾ in air. If A represents the smallest intensity of illumination which the eye can just observe, and x the optical range in metres, i.e. the greatest

⁶⁾ Cf. No. 2 of the literature.

⁷⁾ Cf. No. 6 of the literature.

⁸⁾ As a matter of fact distances are expressed by sailors in miles (1853 m). For this rather theoretical considerations we prefer, however, to use the metre as the unit of length.

distance at which the light can just be observed with a given atmospheric condition, then, due to the spherical propagation of light, there is the following relation between these two quantities:

$$A = \frac{I_e a^x}{x^2} \dots \dots \dots (5)$$

Usable results are obtained with this formula if A is taken equal to 2 · 10⁻⁷ lux; formerly the value 10⁻⁷ lux was used, and instead of the effective the maximum intensity was used, so that formula (5) appeared to be less useful than it actually is.

Visibility curves ⁹⁾.

Since 1907 observations have been made regularly in the Netherlands on the optical range of the different lighthouses in all kinds of weather conditions, so that much empirical data on this subject are available. In practice so-called visibility curves are often used, which may be derived in the following way from formula (5). The formula is written in the logarithmic form:

$$\lg \frac{A}{I_e} = \lg \frac{a^x}{x^2} = \lg \frac{1}{x^2} + x \lg a \dots \dots (6)$$

The following curve may easily be drawn:

$$y = \lg \frac{1}{x^2} = -2 \lg x, \dots \dots \dots (7)$$

as has been done in fig. 15. In addition the straight lines:

⁹⁾ Cf. Nr. 2 and 3 of the literature index.

$$y = (-\lg a) x + \lg \frac{A}{I_e} \dots \dots \dots (8)$$

have also been drawn, which cut the y-axis at points $y = -\lg I_e/A$ and have a slope whose tan-

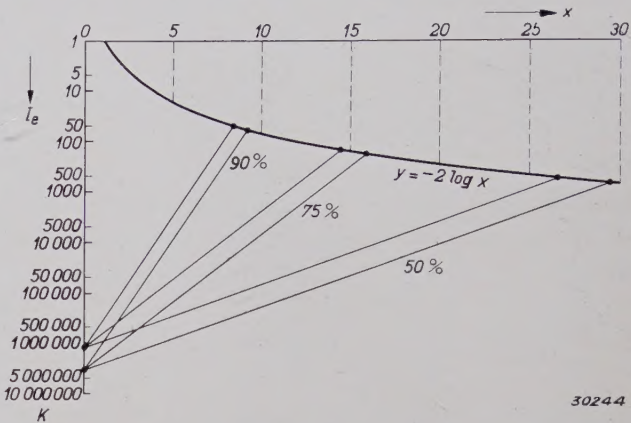


Fig. 15. The optical range x in nautical miles (1 nautical mile = 1855 m) is found as the point of intersection of the curve: $y = -2 \log x$ (formula (7)) with one of the straight lines (formula (8)) whose slope depends only on the transparency of the atmosphere. The intersection of these lines with the negative y-axis is determined by the effective light intensity I_e in candle powers plotted on a logarithmic scale along this axis.

gent is $-\lg a$, which thus depends upon the atmospheric condition. On the negative y-axis the effective light intensity I_e is plotted on a logarithmic scale, while the x-axis is marked off in a linear scale of nautical miles. The optical range of a given lighthouse under given atmospheric conditions is then given by the abscissa of the point of intersection of the curve of formula (7) with one of the straight lines of formula (8), whose intersection

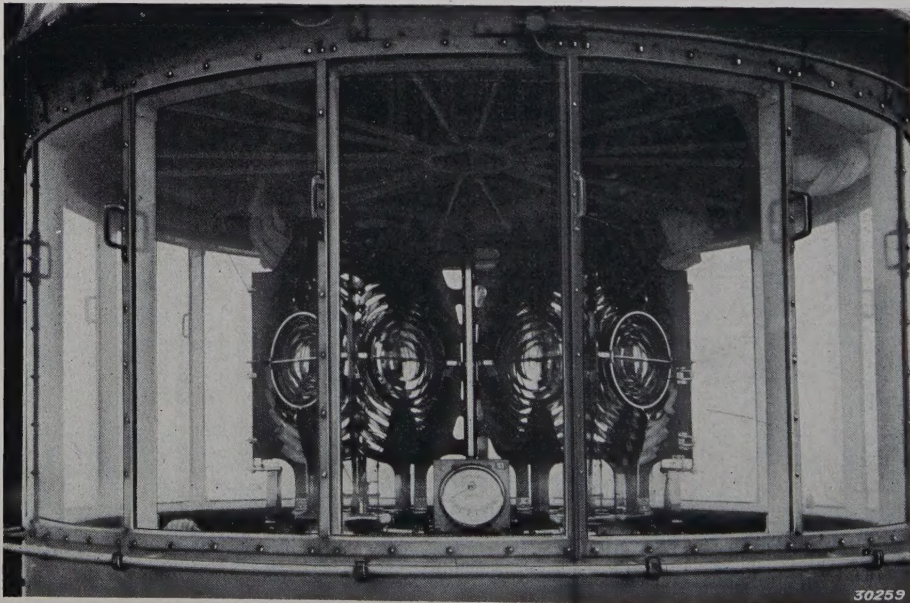


Fig. 16. The double optical system of the Brandaris, the ray diagram of which is drawn in fig. 17.

No.	Filament sytem	Prescribed power	Duration of flash	Maximum light intensity		Effective light intensity	Effective light intensity per optical sytem per 1 000 W
		W	sec	per optical sytem	total		
				10 ⁶ c.p.	10 ⁶ c.p.	10 ⁶ c.p.	10 ⁶ c.p.
1	cross-shaped	4 000	0.30	2.3	4.6	2.14	0.275
2	cylindrical	4 000	0.244	2.78	5.56	2.42	0.302
3	"	3 000	0.234	1.69	2.38	1.44	0.240
4	doubly-spiralized	4 200	0.25	4	8	3.5	0.418
5	"	3 000	0.206	3.5	7	2.84	0.49

In this table the light flux of the lamps with cylindrical filamentsystem has been taken 78 000 and 54 000 lumens (cf. Note on page 31).

with the vertical axis depends upon the effective light intensity of the lighthouse in question, while its slope is determined by the atmospheric condition. The straight lines of formula (8) are drawn in fig. 15 for two different lighthouse lamps (nos. 3 and 4 of the table on page 39), corresponding to three different coefficients of transparency of the atmosphere which are exceeded by the actual value of the transparency coefficient during 50, 75 and 90 per cent of the year.

Calculation of effective light intensity and optical range in a practical case

As a practical example we shall in conclusion calculate the effective light intensity and optical range which are obtained with several of the lamps discussed when they are placed in the optical system (fig. 16) of the Brandaris at Terschelling shown in fig. 5.

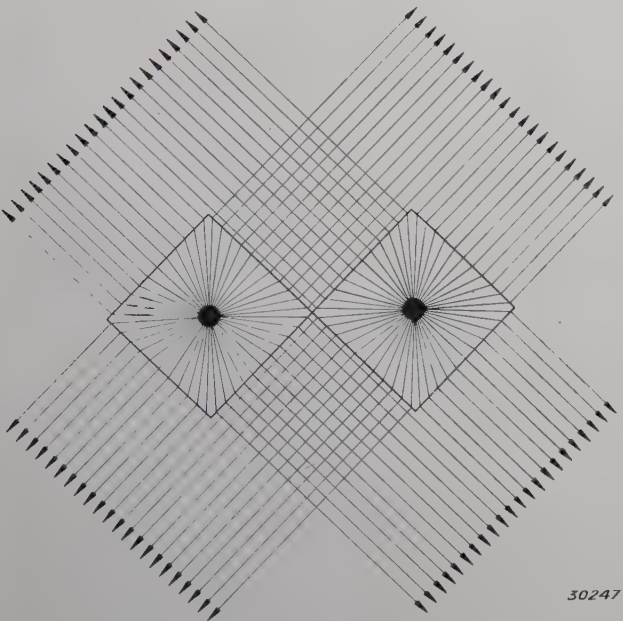


Fig. 17. Diagram of the paths of the rays in a double optical system consisting of two light sources surrounded by four perpendicular panels.

This optical system is a so-called double optical system. It was constructed when the Brandaris was equipped with arc light, and due to the small dimensions of the spot of light with a carbon arc a large enough panel could not be used, since the beams would have become so narrow that the flash time would have been too short. In order to obtain a sufficiently high luminous intensity two optical systems were set up side by side in a manner indicated clearly in fig. 17. Each of the two systems gives four beams in mutually perpendicular directions, which in pairs of two form the four beams of the lighthouse.

Each panel occupies an angle of 90° and has a focal length of 30 cm. We shall now calculate the effective luminous intensity of this double system when the different lamps are used which have already been indicated in the table on page 39. As example we take the doubly spiralized lamp for 70 volts, 60 A, No. 4 in the table. The width of the spiral is 2.35 cm so that with 3 revolutions per minute, according to formula (2), a flash will last

$$t = \frac{2.35/30}{2 \pi \cdot 3} \cdot 60 = 0.25 \text{ sec.}$$

According to the measurements of the Testing Station of the Netherlands Lighthouse Service the maximum light intensity for one optical system was: $I_m = 4 \times 10^6$ c.p., and for the total beam therefore: 8×10^6 c.p. According to formula (3) the effective light intensity then becomes

$$I_e = 0.7 \cdot \frac{0.25 \cdot 8 \cdot 10^6}{0.15 + 0.25} = 3.5 \cdot 10^6 \text{ c.p.}$$

If the same calculation is carried out for the other lamps in the table, the results given in the table below are obtained.

It may be seen from this table that the lighthouse lamp with a doubly-spiralized filament for 4 200 watts burns about 40 per cent more economically than the lamp with the cylindrical filament sys-

tem for 4 000 watts, and about 50 per cent better than the lamp with the cross-shaped filament system for 4 000 watts. Furthermore the lamp with the doubly-spiralized filament for 3 000 watts is found to be 100 per cent more economical than the one with the cylindrical filament system.

In the following table the optical range in nautical miles is given of the various lamps for a visibility occurring during 50, 75 and 90 per cent of the year.

No.	Filament system	Power W	Optical range in nautical miles during:		
			50% of the year	75% of the year	90% of the year
3	cross-shaped	4 000	27.2	15.2	8.1
1	„	4 000	27.2	15.2	8.1
2	cylindrical	3 000	25.2	14.5	7.7
4	doubly- spiralized	4 200	29.5	16.2	8.5
5	„	3 000	28	15.8	8.3

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**PICTURE TAKEN DURING THE ASSEMBLY OF A LARGE FILAMENT LAMP
FOR 110 V, 10 KW.**



THE NIPKOW DISC

by H. RINIA and L. LEBLANS.

621.397.33

After an explanation of the way in which a Nipkow disc is designed for a certain method of scanning, a discussion is given of the technical details of the construction and mounting of the disc. The most difficult problem is that of making the holes, which must be only $27\ \mu$ wide, and of locating them in the correct places. A very satisfactory solution of this problem has been found by making each hole on a separate plate and mounting the thus prepared plates (81 in this case) on the disc in such a way that the holes can be adjusted to the correct position after the disc is fastened in a dividing machine.

A television installation for broadcasting films has been described in two articles in this periodical^{1,2}). The most distinctive feature of this installation is the Nipkow disc for scanning the film. We shall here discuss the problems which arise during the construction of the disc and the way in which the difficulties were met.

The design of the disc

In the first place the size of the disc must be determined, (*i.e.* the diameter of the ring of holes), its speed of rotation, the number of holes necessary and their size. The values determined upon will depend upon the scanning system chosen in the way briefly described below.

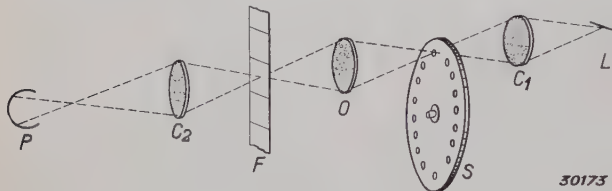


Fig. 1. Arrangement for film scanning with a Nipkow disc. L = linear light source (super high pressure mercury lamp); C_1 = condenser lens; S = Nipkow disc; O = lens which focusses the holes in the disc on the film F ; C_2 condenser lens; P = photocell (electron multiplier).

Fig. 1 is a diagram of the arrangement for scanning. The holes in the rotating disc S are focussed by the lens O on the film F with a certain enlargement which we shall call μ . Since the image of a hole must touch the film just as the image of the preceding hole leaves the film at the other side, the following condition holds for the distance s between the holes:

$$\mu s = b, \quad \dots \dots \dots (1)$$

where b is the width of the film picture. The length of path of the scanning spot which corresponds to the duration of the synchronization signal must be added to the width of the film. If the light spot must scan m lines per picture and N pictures per

second, then Nm holes must pass per second. The speed V_s of the disc at the position of the holes (*i.e.* approximately the peripheral velocity) must be:

$$V_s = Nm s = Nm b \frac{1}{\mu} \dots \dots \dots (2)$$

If a given enlargement μ is chosen the peripheral velocity of the disc is thereby determined. At the same time the diameter g of the holes is also determined since the image of the hole must have a diameter equal to the distance between the lines in scanning.³). On one film picture, height h , m lines are scanned, therefore

$$g = \frac{h}{m} \cdot \frac{1}{\mu} \dots \dots \dots (3)$$

What value should be chosen for the enlargement μ ? If μ is made very large, then according to equation (3) the holes must be very small. With h equal to 16 mm, $m = 405$ lines and an enlargement of $\mu = 4$, a hole diameter of $g \approx 0.01$ mm is arrived at. Such small holes are practically impossible to make because of the great accuracy required.

If on the other hand μ is small, then according to equation (2) the peripheral velocity of the disc must be very great. With a maximum width $b = 23$ mm of the film picture to be scanned, $m = 405$, $N = 25$ pictures per second, and an enlargement of $\mu = 0.5$, a peripheral velocity of $V_s \approx 400$ m/sec is obtained. This is almost the velocity of a projectile from a gun. The centrifugal forces become so great (with a disc diameter of 40 cm they are 80 000 times as great at the circumference as the force of gravity), that there is a chance of permanent deformation or even explosion of the disc.

In the choice of enlargement μ a compromise must therefore be found, such that on the one hand the speed of the disc is not too great, and on the

¹) H. Rinia and C. Dorsman, Philips techn. Rev. 2, 72, 1937.

²) H. Rinia, Philips techn. Rev. 3, 289, 1938.

³) Actually this condition only holds for square holes. For practical reasons, however, the holes are made circular. The actual diameter is then chosen somewhat larger than that here derived theoretically, so that the lines overlap somewhat.

other hand the holes are not too small. For the installation in the Philips laboratory μ was chosen equal to 1.7, so that $V_s \approx 140$ m/sec and $g \approx 0.025$ mm.

A similar value of μ is also reached in quite a different way by finding out how the light flux Φ on the scanning spot depends upon μ , and then making Φ as large as possible.

We consider the position and size (h/m) of the image of the hole constant and vary the enlargement μ by moving the lens O , i.e. by changing the distance q (see fig. 2). At the same

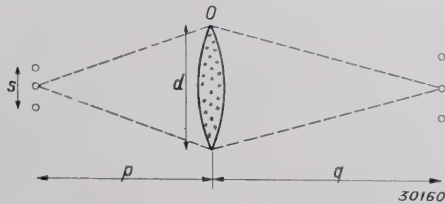


Fig. 2. The lens O , diameter d and focal length f , focusses the holes in the Nipkow disc on the film with an enlargement μ . With a width of film b and a distance between the holes s , $\mu s = b$. We assume that the enlargement μ is varied by changing the distance g between lens and film and then changing s and p correspondingly in each case.

time the position of the disc (distance p) and the size of the holes must be of course also be changed in order to satisfy the condition for obtaining a sharp image⁴):

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q} \dots \dots \dots (4)$$

(f is the focal length of the lens O) and also to satisfy equation (3). The only change which is observable on the film as a result of this manipulation is a change in the solid angle φ of the beam thrown on the film by the lens O . The amount of light Φ is in this case proportional to the solid angle:

$$\Phi = \text{const.} \frac{\pi d^2}{4 q^2},$$

where d is the diameter of the lens. From (4) it follows that

$$q = f \left(1 + \frac{q}{p} \right),$$

and since q/p is equal to the enlargement $b/s = \mu$, we obtain

$$\Phi \propto \left(\frac{d/f}{1 + \mu} \right)^2 \dots \dots \dots (5)$$

With a lens with a given relative aperture d/f , Φ is thus proportional to $(1 + \mu)^{-2}$. This function is drawn in fig. 3 with the reciprocal of the enlargement $1/\mu$ as abscissa. From equations (2) and (3) it may be seen that this curve also represents the dependence of the amount of light on the speed of the disc V_s or on the size g of the holes. With infinite enlargement ($p = f$, $V_s = 0$ and $g = 0$) Φ is equal to zero; when μ decreases, Φ at first increases with the square of $1/\mu$, thus proportional to V_s^2 . The increase of Φ then becomes slower, and at $\mu = 2$, Φ increases only proportional to $1/\mu$ (thus $\propto V_s$). It is therefore of little additional advantage to choose μ much smaller than 2.⁵).

Moreover the amount of light no longer forms a difficulty. Since the publication of the article quoted in the first footnote, where it was shown that when a super high pressure mercury lamp was used as a source of light (L in fig. 1) a more than adequate amount of light was available, the brightness of the super high pressure mercury lamp has been increased by a factor 3 (it is now about 90 000 c.p./sq.cm), so that from this point of view a larger value of μ (smaller V_s) could also be used if it were not that the holes would then have to be too small.

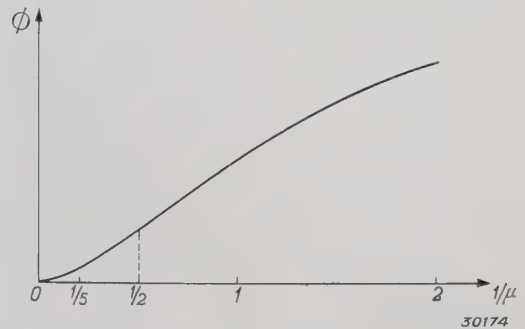


Fig. 3. Variation of the light flux Φ (in arbitrary units) on the scanning spot on the film, as a function of the reciprocal of the enlargement $1/\mu$ (the latter is proportional to the required peripheral speed of the disc, V_s , and the required size of the holes g).

When the enlargement μ and therefore also the diameter of the holes g and the speed of the disc V_s are determined, the radius r of the ring of holes must be chosen. It is best not to make r too large in order not to obtain too heavy a disc with correspondingly heavy driving motor and large bearings. On the other hand r may also not be too small, since in connection with the scanning it is necessary that the arc of a circle between two holes may be regarded as a straight line. With the radius $r = 17.5$ cm which we have chosen this latter condition is adequately fulfilled.

The necessary number G of holes in the disc and the required number of revolutions n per second now follow from the equations (see also equation (1)):

$$G \cdot s = 2 \pi r$$

and

$$2 \pi r \cdot n = V_s.$$

The results obtained are $G = 81$ and $n = 125$ revolutions per second⁶).

Mounting of the disc

The required high speed of the disc makes it necessary that it be rotated in an atmosphere at

ever, a sharp limit appeared for the amount of light, while in the case here imagined a gradual slowing up of the increase occurred instead.

⁶) Because of the necessary synchronization, one is actually bound by the condition that the number of revolutions of the disc and of the film motor (50 r.p.s.) must have a simple relation, for example $n = 75$, $n = 100$, $n = 125$, $n = 150$, etc. One has therefore only to choose between a number of discrete values of r which are hereby determined.

⁴) We naturally neglect spherical aberration in this case. Actually the lens must be specially corrected for every enlargement because of this factor.

⁵) In the article cited in footnote 1) a similar result is derived by means of a different hypothetical experiment, in which the lens O was replaced by a system of two lenses. There also it was found that the amount of light at first increases with the square of the speed of the disc, with $\mu = 1$, how-

reduced pressure. If it should rotate in air at atmospheric pressure, the overcoming of the friction of the air would require an amount of energy of $\frac{1}{2}$ to 1 kW. Moreover the great heat development might be dangerous for the disc, since it must rotate in a closed space in order that the holes may remain clean and for the sake of safety, and the heat is therefore not easily dissipated. At the pressure chosen of about 1 cm of mercury the heat of friction is less than 30 W. The pressure could not be made much lower than 1 cm since the disc is very strongly irradiated in the neighbourhood of the holes during use, and a certain layer of air is

into the evacuated space. The pressure of the atmosphere on the oil tends of course to press it into box *A*. The film of oil around the shaft in the first bearing is, however, so thin (about 2μ) that its resistance to flow is high enough to prevent any large quantity of lubricating oil being pressed into box *A*, in spite of the fact that very thin oil must be used because of the friction at the high speed of revolution (7 500 r.p.m.). It has been found in practice that less than 1 cc of oil per hour leaks into the vacuum. A ring around the shaft prevents this oil from reaching the Nipkow disc and causes it to flow off into a small reservoir.

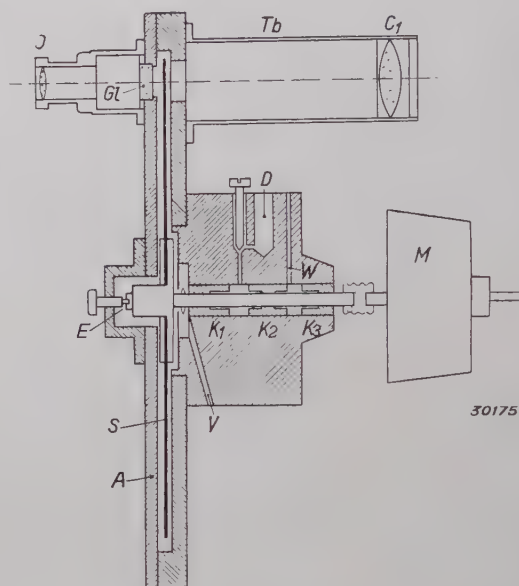
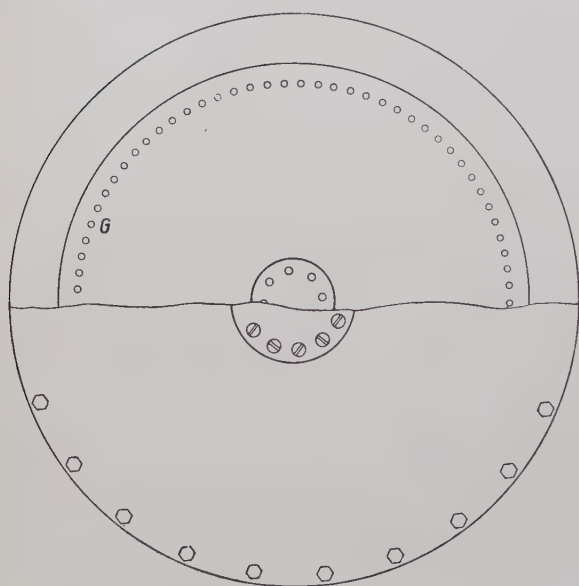


Fig. 4. Set-up of the Nipkow disc *S* in the evacuated iron box *A*. The shaft turns in three bearings K_1 , K_2 and K_3 . K_1 also serves as gas-tight seal. *D* = oil reservoir; *W* = outlet tube; *E* = pressure bearing (see fig. 5); *M* = motor; *O* = lens (a camera objective); *Gl* = glass plate as vacuum seal. On the other side of the disc this glass plate with its accompanying loss of light is avoided by fastening the condenser lens C_1 in the tube *Tb* to the box *A* by an air-tight joint; *G* = ring of holes.

necessary in order that the disc may give off the heat developed.

The disc *S* therefore rotates in an evacuated iron box *A*, see fig. 4. This box is quite heavily constructed so that in case the disc should break the pieces cannot escape.

Bearings

The axle of the disc turns in three bearings, K_1 , K_2 , K_3 which are lubricated with oil. They must also serve as gas-tight seals for the box *A*. The foremost bearing K_1 is therefore made to fit extremely accurately, which is also necessary for smooth running of the disc. Furthermore the space between the bearings is completely filled with oil which is supplied from the reservoir *D*. No air can therefore pass the bearings and penetrate

The middle bearing K_2 is introduced to keep the shaft turning true. The shaft is also made very thin because of friction. The hole *W* serves to allow the air to escape when the bearings are filled with oil, so that the space between the second and third bearings K_2 and K_3 is always filled with oil. The extremity of the shaft is connected with the driving motor by means of a flexible coupling made of tombac.

On the opposite side of the disc the shaft does not extend outside the box. Here it must experience a pressure opposite to the inward force of the unilateral air pressure. In order to avoid any possible difficulties of lubrication a ball bearing (*E*) is here used like that represented in fig. 5 twice its actual size. Because of the large centrifugal forces it was necessary to make this ball bearing as small as

possible. It consists of a ball race with three balls 1 mm in diameter against which the flat, ground surface of a hard steel pin presses. This pin is fastened to the end of the shaft. The balls roll on the flat ground surface of a half ball of a larger size which rests against a ring. This type of bearing ensures the smooth running of the disc, since the plane surface on which the balls roll can adjust itself automatically to all positions.

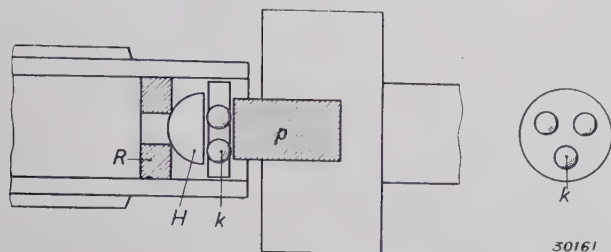


Fig. 5. Ball bearing (*E* in fig. 4), which holds back the shaft of the disc pressed inward by air pressure. Three balls *k* turn between the end surface of a pin *p* in the shaft and the plane ground side of a half ball *H* which rests against a ring *R*. This latter surface can adjust itself automatically in all positions. Because of the high centrifugal forces the ball bearing is made very small (here drawn about twice its actual size).

Material of the disc

Aluminium was chosen as material for the disc. This material has the advantage that the disc can be made absolutely flat and free of stress, simply by heating it between two iron discs. It is obvious that absolute freedom from stresses is an essential requirement. In order to obtain accurate scanning through the holes the distance of the holes from the centre must be accurate within 5μ . Upon rotation of the disc a deformation takes place due to the stresses from centrifugal forces, in the sense that the holes are displaced away from the centre. This can easily be observed when the holes in the rotating disc are examined through a microscope. A thin line is seen which is displaced toward the circumference when the speed of rotation is increased. In order to satisfy the above-mentioned condition about the radial position of the holes, the displacement must be the same for all the holes, i.e. only symmetrical rotational deformations are permissible. Therefore there must be no (unevenly distributed) initial stresses in the disc which, when the centrifugal forces are added, might lead to a local stress exceeding of the limit of elasticity or even of the yield value.

Another advantage of aluminium is its good heat conductivity which prevents local overheating due to the irradiation. The strength of the material is also more than adequate to withstand the stresses due to the centrifugal forces. The greatest stresses

occurring in the disc, which can be determined directly by means of the above-mentioned experiment, are about 1 kg/sq.mm at the usual speed of rotation, while the permissible loading of aluminium amounts to 6 kg/sq.mm.

Making the holes

By far the most difficult problem in the construction of the Nipkow disc is the making of the 81 holes and locating them in the proper places. In addition to the above-mentioned requirement that the position of the holes may show deviations of not more than 5μ in the radial direction, the distance between the holes must also be equally accurate. Furthermore it is very important that all the holes allow exactly the same amount of light to pass through in order to obtain a picture of uniform brightness. Therefore the diameter of the holes, which is chosen at 27μ , must be accurate within 1 per cent. With greater deviations than this the eye already observes disturbing differences in brilliance of the different lines.

The most obvious method is that of punching the holes in thin foil. Such a hole is shown diagrammatically in fig. 6, and a number of light rays coming from different directions are also indicated. It may be seen that the effective aperture of the hole is smaller for the obliquely incident rays (*bb* and *cc*) than for the normal rays (*aa*). The difference in effective aperture due to the different angles of incidence depends upon the depth of the hole. This can, especially with a very divergent beam, lead to differences in the amount of light transmitted, since the depth of the holes may vary slightly due to burrs which occur in punching. The reduction of the effective aperture for oblique rays is indeed partially compensated for by the fact that some rays (*b'b'*, for instance) are reflected. Nevertheless

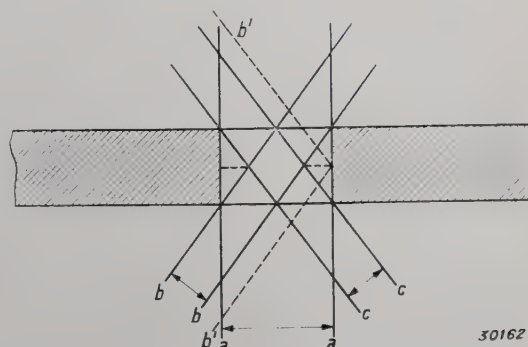


Fig. 6. Punched hole. For obliquely incident rays (*bb*, *cc*) the effective aperture is smaller than for beams normal to the surface (*aa*). The difference in amount of light transmitted caused by the differences in angle of incidence depends upon the depth of the hole. The reflection at the walls (*b'b'*) compensates this effect to some extent but is, however, dependent upon the condition of the wall.

this compensation is different for the different holes, since the reflective power of the walls of the holes may vary very much. It is therefore advisable to limit the whole effect to a minimum by making the hole as shallow as possible. A disc was first made by the authors on which the holes were punched in duraluminium of $5\ \mu$. Fair results were obtained with this disc but it was found difficult

steel plate P about 2 mm in diameter and 0.3 mm thick a conical depression was made with a sharp point (*fig. 7a*). The plate was hardened and then ground so that a hole occurred at the point of the cone. It was finally polished until the hole G had exactly the correct diameter of $27\ \mu$. This latter operation was checked indirectly by allowing light to fall on the plate and then by means of a

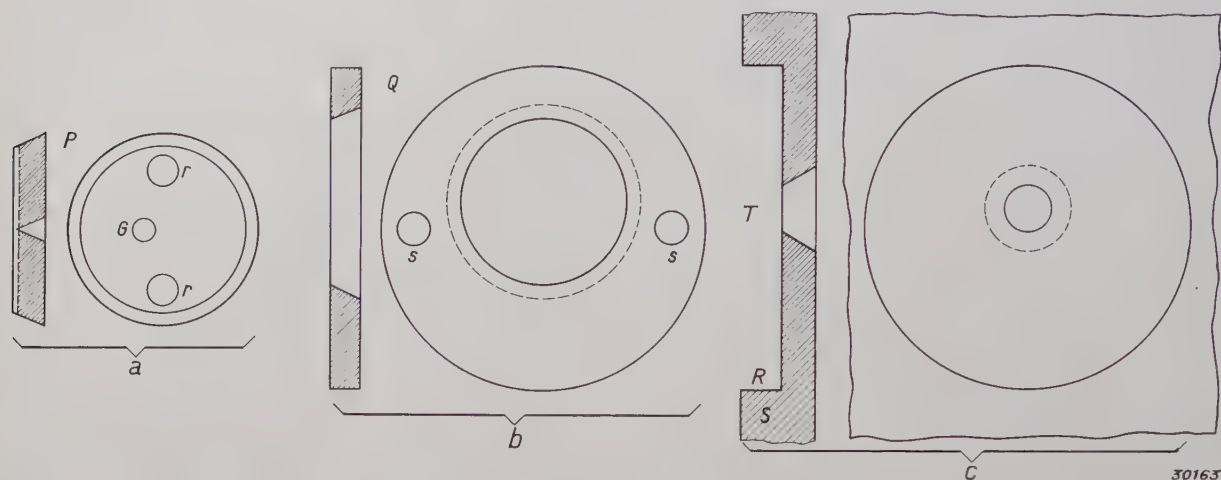


Fig. 7. Making and mounting the holes in the Nipkow disc.

- A conical depression is made in an unhardened steel plate P . After hardening the plate is ground so that a hole G is formed at the apex of the cone. This hole is given the required diameter by polishing.
- Duraluminium plate Q with a conical opening into which the conical outer surface of plate P fits.
- Piece of the Nipkow disc S with circular depression R cut out, into which plate Q exactly fits. Conical hole T bored at about the place where the hole G must be.

to rid the holes of dust or other contaminations, because the foil is weak and the capillary forces which hold a drop of liquid in the holes are very large.

For that reason we adopted the following method of construction. In a small unhardened circular

photocell and amplifier measuring the amount of light passing through the hole. 81 holes were made in this way and were mounted on the disc in a manner which will be described later.

The edges of the holes obtained are sharp so that fuzziness is avoided. The photomicrograph *fig. 8* shows a cross section of a plate through the hole. The cut surface has been ground in order to show the sharp boundary of the hole at the point of the cone. The holes can now easily be cleaned since the plates are extraordinarily strong in contrast to the earlier used extremely delicate foil. A further important advantage of the method is that each hole can be replaced separately in case of defect or damage.

The correct placing of the holes

The method of mounting the holes at the correct places on the Nipkow disc is the following. The holes are not exactly at the centres of the plates P but slightly excentric, as may be seen clearly in *fig. 7a*. The steel plate P which has a conical outside surface is not fastened directly to the Nipkow disc but is placed in a conical cavity of a larger cir-

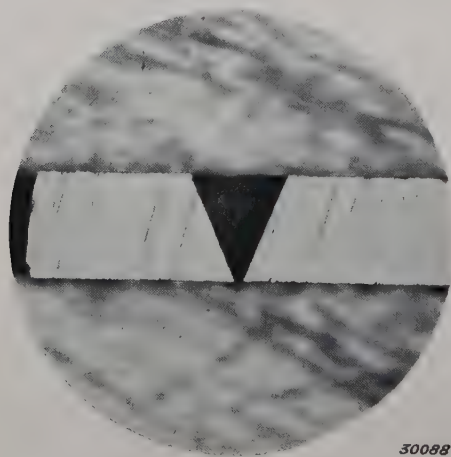


Fig. 8. Photomicrograph of the ground surface cut through a plate P (magnification 30 times). The sharp boundary of the hole G at the apex of the cone may be seen. The edge is actually still sharper than is shown here since it has been broken away slightly by the grinding of the cut surface.

cular plate Q of duraluminum, in which it fits exactly but projects slightly. The cavity in Q is also excentric, see fig. 7b. Plate Q in turn fits exactly into a circular depression R which is cut out of the Nipkow disc at approximately the place where there must be a hole, fig. 7c. A conical hole T is here bored through the disc.

When plates P and Q are put together and placed in the depression R , the edge of the latter is forced slightly over the edge of plate Q , so that Q and at the same time P are held fixed. Both plates can now however still be turned by means of small keys which fit into the openings rr and ss . By means of the double excentric the hole G can be given any position within a certain ring-shaped area, and a correct placing of the holes is thus easily attained. This is more clearly illustrated in fig. 9 where only the lines joining the pivot points and the hole G on the plates P and Q are drawn. The hole G is fastened as it were to the free end of two hinged bars of lengths a and b . The ring-shaped surface which can be compassed is shaded. By placing the excentrics at such an angle that b and a' are perpendicular at the rough adjustment, the displacements caused by the turning of both of the excentrics are perpendicular to each other, which makes the correct placing very simple, especially if a is made equal to $b/2$, so that in the position drawn $b = a'$, and turning of the two excentrics through equal angles gives equal displacements. In practice a was chosen 0.35 mm and b , 0.25 mm; the distance of the holes from the axis of the disc can thus be varied by 0.6 mm. The permissible deviations during construction are therefore considerably greater than if the holes were made directly in the

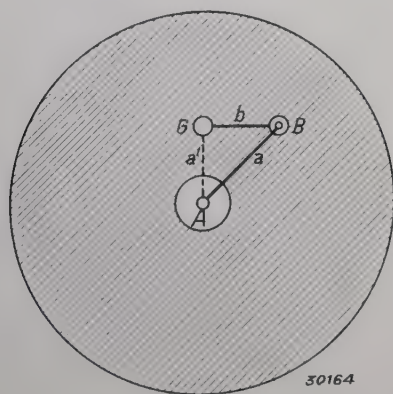


Fig. 9. Diagram showing the principle of the method of correct placing of the holes. The hole G is excentric in the plate P (fig. 7a) and this plate in turn is excentric in plate Q (fig. 7b). Both plates can be turned. This is equivalent to fastening the hole G to the end of two hinged bars a and b with the pivotal points A and B . By a suitable position of the bars G can be placed at any point within the shaded ring.

disc. In fig. 10 the arrangement of the excentrics on the Nipkow disc is again shown in its entirety.

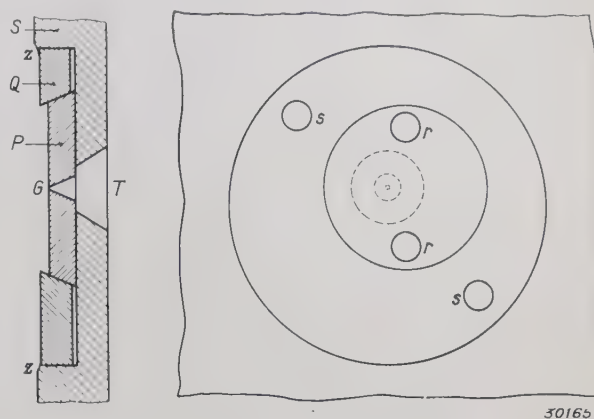


Fig. 10. Arrangement of the two excentrics mounted on the disc. The edge z of the depression in S is forced slightly over Q , so that the whole is fixed except for a possible rotation of P and Q by means of small keys which fit in the holes rr and ss respectively.

After the holes G have been placed at approximately the correct positions, the precise adjustment takes place on a dividing machine. It was found necessary to maintain a constant temperature within 1° during this fairly lengthy operation, in order not to introduce errors due to the different degrees of expansion of the disc and the dividing machine. The accuracy thus attained in the position of the holes is considerably higher than the requirement, the deviations do not amount to more than 2μ . When the disc is in use the temperature may be neglected since because of the rapid rotation, and even with the above-mentioned strong local heating, the temperature distribution exhibits a rotational symmetry.

After the correct placing of the holes the plates are fixed with a small amount of lacquer. This is necessary because of the strong centrifugal forces which occur during rotation. These forces do not indeed exert a couple on the plates in the first instance, but because of the lack of symmetry in the plates slight displacements might occur if vibrations should set in, and such displacements would destroy the work of placing the holes.

The high centrifugal forces also make it necessary that the disc be very carefully balanced. An unbalanced weight of 1 g at the circumference of the disc would experience a force of more than 10 kg when the disc is turning at its usual speed! Balancing is facilitated by the fact that the whole mass of the disc lies in the neighbourhood of one plane. No bending forces therefore are to be expected upon rotation, and the disc can be satisfactorily balanced statically.

TIME LAG PHENOMENA IN GAS-FILLED PHOTOELECTRIC CELLS

by A. A. KRUTHOF.

621.383.2.032.12

In many applications of photocells the ratio of noise to signal can be made smaller by amplifying the photocurrents already *in the cell*. This may be done by filling the cell with gas; the photoelectrons are then multiplied by the ionization of the gas. Due to the finite transit time of the ions formed, the cell shows a time lag which causes a sharp fall in the frequency characteristic of the cell at high frequencies. The time lag increases with the amplification factor. If this is smaller than 10, the time lag is insignificant up to frequencies of about 10 000 cycles/sec, so that gas-filled cells may be used for sound film. The theoretically derived frequency characteristics of the cells are confirmed in the main by measurements. An experimentally found extra time lag at lower frequencies (1 000–5 000 c/s) is explained as due to a contribution to the amplification by metastable atoms.

The direct transformation of light into electric current by means of photocells was soon put to many uses, for example for the measurement of quantities of light in the photometer, for the operation of light relays in signal lights and safety devices, etc. The photoelectrically sensitive material originally used was selenium. When, however, new applications of the photoelectric effect appeared, such as sound film and television, where rapidly changing quantities of light had to be transformed into electric voltage fluctuations, selenium was no longer found satisfactory. The photoelectric effect with this material is accompanied by a certain time lag. In the first mentioned applications (photometer, light relay) this factor was not important. If, however, a sinusoidally modulated light flux is allowed to fall on a selenium cell, then due to the inertia the fluctuations are smoothed out to some extent, so that the photocurrent obtained shows a smaller depth of modulation than the light flux. The decrease in the depth of modulation will be greater, the higher the frequency of the light modulation and the greater the inertia of the cell. In the case of the sound film frequencies up to about 10 000 cycles/sec, and in television even up to $3 \cdot 10^6$ cycles/sec must be reproduced, so that only those photocells can be used for this purpose which have a sufficiently small time lag.

In modern photocells the external photoelectric effect of alkali metal atoms adsorbed on an oxide layer¹⁾ is used: electrons are freed by the light which falls on this sensitive surface, the cathode, and are drawn toward the anode by means of an accelerating voltage. Such a photoelectric cathode in an evacuated bulb gives a transformation of light into electric current which is practically free from inertia.

The sensitivity of these modern photocells may

amount to 20 $\mu\text{A}/\text{lm}$ for example in a practical case. The maximum intensity of illumination which the cathode can withstand in use without permanent injury is, however, relatively small, namely only some thousandths of a lumen per sq.cm. A cell of reasonable dimensions can therefore not be allowed to give a larger photocurrent than about 5 μA even when an unlimited amount of light is available. The photocurrent is usually a great deal smaller, because of the fact that the amount of light available in the apparatus is limited. It is clear that this photocurrent must first be amplified for practical applications²⁾.

Amplification of the photoelectric current

The diagram of a commonly-used connection of a photocell with an amplifier is given in fig. 1.

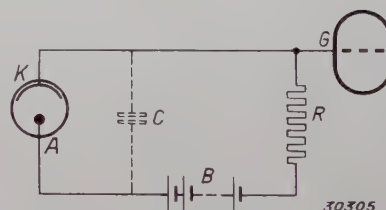


Fig. 1. Diagram of the connection of a photocell with an amplifier. K = photocathode, A = anode, B = source of accelerating voltage, R = coupling resistance, G = grid of the first amplifier valve, C = capacity of the cell and connections.

A background noise is present in the voltage obtained on the resistance R , which may be ascribed mainly to³⁾:

a) The thermal motion of the electrons in resistance R ;

²⁾ H. Rinia and C. Dorsman, Television system with Nipkow disc, Philips techn. Rev. 2, 72, 1937; A. L. Timmer and A. H. van Assum, A surveyance system using infrared rays, Philips techn. Rev. 1, 306, 1936.

³⁾ M. Ziegler, The cause of noise in amplifiers, Philips techn. Rev. 2, 136, 1937; Noise in amplifiers contributed by the valves, Philips techn. Rev. 2, 329, 1937.

¹⁾ M. C. Teves, The photoelectric effect and its application in photoelectric cells, Philips techn. Rev. 2, 13, 1937.

b) The fact that the negative charge is emitted by the cathode K of the photocell, not in the form of a continuous current, but in the form of discrete amounts of charge, the electrons (shot effect).

The first effect mentioned causes a voltage fluctuation whose mean square is given for every frequency band of the width $\Delta\nu$ by the following:

$$V^2 = 4 k T R \Delta\nu; \quad \cdot \cdot \cdot \cdot \cdot \quad (1)$$

k is the Boltzmann constant and T the absolute temperature. The shot effect causes a current fluctuation whose mean square, again considered for the band of width $\Delta\nu$, is proportional to the average photocurrent:

$$I^2 = F^2 \cdot 2 e I_f \Delta\nu \cdot \cdot \cdot \cdot \cdot \quad (2)$$

In this expression e is the charge of the electron and F^2 the so-called noise factor ($F^2 < 1$) which expresses the fact that the shot effect is partially neutralized by the space charge. F^2 depends upon the anode voltage of the photocell. The square of the total noise voltage on the resistance R becomes

$$(4 k T R + F^2 \cdot 2 e I_f R^2) \Delta\nu.$$

The square of the signal voltage on the resistance R is $I_w^2 R^2$, where the effective alternating photocurrent is given by

$$I_w^2 = (\bar{I_f} - \bar{I_f})^2.$$

For the ratio of the energies of noise and signal the following is obtained when the noise contributions of all the frequencies passed by the amplifier are added:

$$G \cdot \frac{4 k T R + F^2 \cdot 2 e I_f R^2}{I_w^2 R^2}, \quad \cdot \cdot \cdot \cdot \cdot \quad (3)$$

where the proportionality factor G depends upon the frequency characteristic of the amplifier.

If the anode voltage V_a is chosen so that the photocurrent I_f reaches its saturation value — this is the most important practical case — then F^2 becomes equal to 1. By filling in the numerical values for e and k , when T is set equal to 300 °K (*i.e.* room temperature), the following is obtained:

$$G \cdot \frac{0.052 + I_f R}{I_w^2 R} \cdot \cdot \cdot \cdot \cdot \quad (4)$$

$\bar{I_f}$ and I_w are in amperes and R in ohms.

For good quality in reproduction it is important to make the ratio of noise to signal given by (4) as small as possible. This is accomplished in the first instance by choosing R large. A limit is, however, set to the size of R due to the capacity of the cell and the supply lines which are often screened. In fig. 1 this capacity is shown dotted. With too large a value of R the RC time of the circuit (*i.e.* the charging time of the "condenser" C) would become too great with the result that attenuation of the high frequencies would occur. Practically, the coupling resistance R must not exceed 100 000 ohms in the case of sound film and must be smaller than a few thousand ohms in the case of television ²⁾.

The second term in the numerator of (4) usually has a value between 0.01 and 0.1 in the application for sound film. If the amplifier itself gives appreciable noise, this must be taken into account by increasing the resistance R in the first term of the numerator of (3) by the so-called noise resistance of the amplifier. The first term (thermal voltage fluctuations) in most cases makes a large contribution to the noise. In the case of television the first term is always much larger than the second.

In the case where fluctuations outside the cell (first term) dominate over those inside the cell (shot effect, second term) the ratio of noise to signal is improved by amplifying the photocurrent already *in the cell*. If in this way the photocell is made to give an anode current $I_a = N \cdot I_f$, then, although the noise from the shot effect increases approximately with the square of N ⁴⁾, the ratio (4) becomes smaller:

$$G \cdot \frac{0.052 + N^2 I_f R}{N^2 I_w^2 R} = G \cdot \frac{0.052/N^2 + I_f R}{I_w^2 R}.$$

If the first term of (4) is large compared with the second, (4) decreases inversely proportional to N^2 . Moreover there is the not unimportant advantage that for a given output voltage an N times smaller amplification following the cell is sufficient, so that it becomes easier to reduce the hum of the amplifier satisfactorily.

An amplification of the photoelectric current *in the cell* may be attained by causing a multiplication of the electrons on their way from cathode to anode. There are two possible methods of doing this:

⁴⁾ In formula (2) not only I_f but also the effective elementary charge e are multiplied by a factor N ; in the practical realization of the multiplication of photoelectrons to be described later the factor N is determined only statistically, so that the increase of the shot effect is somewhat more rapid than with the square of N .

- 1) Multiplication by secondary emission. Specially constructed cells are necessary for this method. An "electron multiplier" which uses secondary emission has already been described in this periodical⁵⁾.
- 2) Multiplication by ionization of a gas. This method necessitates no change in the ordinary construction of vacuum cells, a small amount of gas only is added to the cell. In order to avoid chemical action of the gas on the photocathode, an inert gas, usually argon, is chosen for the filling.

Gas-filled photocells have the advantage that considerably higher currents are obtained without the cells becoming more complicated than the original vacuum cells. A disadvantage is, however, that gas-filled photocells, in contrast to vacuum cells, exhibit a certain time lag. We shall now examine the causes of this timelag and see to what degree it restricts the possibility of application of the gas-filled cells.

Mechanism of amplification by ionization

When the photoelectrons, which have been freed by the light incident on the cathode, have been sufficiently accelerated they will be able to ionize atoms of the gas upon collision. In order to do this the accelerating voltage must be higher than the ionization potential of the gas, which in the case of argon is 16 volts. The electrons newly formed by ionization form an amplification of the primary photocurrent.

How many ionizations does a photoelectron cause in the argon on its way to the anode? The number depends in the first place on the accelerating voltage V_a , and further on the configuration of the electrodes and on the density of the gas. The number of ionizations increases when V_a is increased: if V_a is more than twice the ionization potential, the electron which has used up its energy in one ionization process may again be accelerated and cause more ionizations. The electron set free in the first ionization is also accelerated and causes ionizations just as every electron freed by any further ionization, so that instead of one primary photoelectron a whole "avalanche of electrons" arrives at the anode. The greater V_a the more the avalanche can increase on its way. V_a is usually chosen equal to 100 volts.

The influence of the configuration on ionization is best studied in the simple case where two plane

parallel plates are set up in the gas (at a distance of 1 cm for instance.) The dependence of the number of electrons n of the avalanche on the density of the gas is represented in this case by the curve⁶⁾

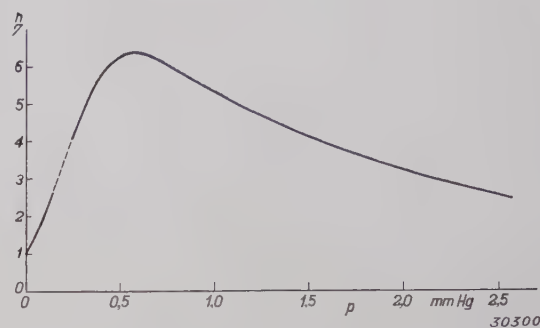


Fig. 2. Number of electrons n of the avalanche caused by one photoelectron between two plane parallel electrodes 1 cm apart in argon at the pressure p . The accelerating voltage was $V_a = 100$ volts.

of fig. 2. At very low gas pressure (low density) the ionization is small since the electrons meet few atoms along their path, and n therefore differs only little from unity. With increasing pressure p the number of ionizations increases, and it increases more rapidly than in proportion to p since the new electrons which are freed by the ionization in turn cause ionisations. If the pressure is continually increased the free path of the electrons between two collisions becomes shorter and shorter. The number of collisions in which the electron has not yet sufficient energy for the ionization of a gas atom increases sharply, and with it, the chance that the electrons give up their energy to the gas atoms in smaller amounts as energy of excitation. Since the energy of excitation is lost for ionization, the curve in fig. 2, after passing a maximum (at $p = 0.55$ mm Hg), begins to fall again.

In the practical construction of the photocells the cathode is usually part of a cylinder, while the anode consists of one or more metal wires or rods. If it is desired to calculate the number of ionizations for this configuration, it must be taken into account that the field strength between cathode and anode is not everywhere the same. Moreover in this case the total path of the electrons is longer on the average than the distance from cathode to anode. The electrons will pass by the anode several times before they are captured.

Until now we have only considered the newly formed electrons. The ions formed will also contrib-

⁵⁾ J. L. H. Jonker and M. C. Teves, Technical applications of secondary emission, Philips techn. Rev. **3**, 133, 1938.

⁶⁾ The data for the left-hand side of the curve are given in: P. T. Smith, Phys. Rev. **36**, 1293, 1930; those for the right-hand side in: A. A. Kruithof and F. M. Penning, Physica **3**, 515, 1936. The two parts of the curve are joined by the dotted line.

ute something to the increase of the electron current, since they move toward the cathode and liberate electrons from it. Because of their greater mass, however, the ions have a much lower speed than the electrons, so that the electrons freed from the cathode by ions will follow the primary photoelectrons with a certain delay. The same process is repeated with these newly formed electrons and with the ions which they form in turn, so that a second, third, etc. group of electrons follow with ever increasing time lags. This phenomenon is the cause of the time lag in gas-filled photocells.

The total amplification

We shall first attempt to discover the degree of multiplication which is finally attained, *i.e.* the amount of charge which is obtained for one photoelectron. Every electron avalanche which occurs as the immediate result of the emission of one electron by the cathode into the gas contains n electrons. At the same time $n-1$ ions have been formed in the gas which move toward the cathode. The number of electrons liberated from the cathode per ion we shall call γ . The $n-1$ ions thus liberate $\gamma (n-1)$ electrons, which are again multiplied in the gas to $n \gamma (n-1)$. $\gamma (n-1)^2$ new ions are then formed which again free $\gamma^2 (n-1)^2$ electrons from the cathode, etc. The total number of electrons which per photoelectron flow through the cell is therefore

$$N = n + n (n-1) \gamma + n (n-1)^2 \gamma^2 + \dots (5)$$

N is called the amplification factor. The sum of the geometrical series (5) has a finite value, if the ratio $\gamma (n-1) < 1$. Then

$$N = \frac{n}{1-\gamma (n-1)} \dots \dots \dots (6)$$

If $\gamma (n-1) = 1$, N becomes infinite, breakdown occurs in the cell. This is the case practically when

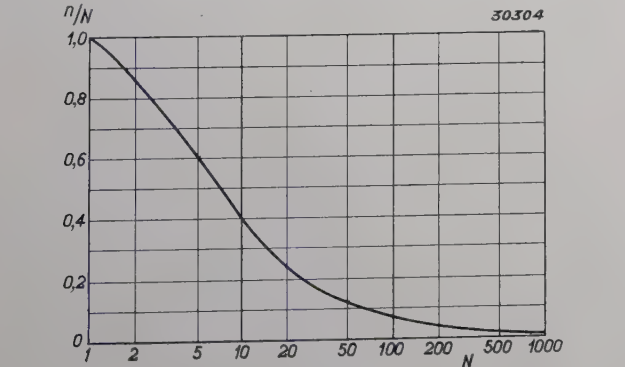


Fig. 3. The ratio n/N of the number of electrons per avalanche to the total amplification as a function of the total amplification N . It is assumed that on the average 0.2 electron ($\gamma = 0.2$) is freed per ion striking the cathode.

n is made too large by increasing the accelerating voltage. For a photocathode $\gamma = 1/3$ to $1/6$. Breakdown therefore occurs at $n = 4$ to 7 .
The part of the electron current which is formed without the agency of ions is n/N . This part shows practically no time lag with respect to the incident light. In *fig. 3* n/N is plotted as a function of N according to equation (6) for the case where $\gamma = 0.2$.

Influence of the transit time of the ions

For the remaining part $(N-n)/N$ of the current we may assume an average length of time which, roughly estimated, will be several times greater than the time τ_i necessary for an ion to move from the place where it was formed in the gas to the cathode. The number of ion transit times before the current caused by one photoelectron has fallen to an insignificant fraction (1 per cent for instance) of its initial value is determined by the ratio $\gamma (n-1)$ of the series (5). At $N = 10$ and $\gamma = 0.2$ (see *fig. 3*) $\gamma (n-1)$ is equal to 0.6, therefore $[\gamma (n-1)]^{10} \approx 0.01$, *i.e.* after 10 ion transit times the current has practically disappeared. The transit time depends upon the anode voltage, gas pressure and the separation of the electrodes. For a definite case which we shall use later, it amounts to $3.5 \cdot 10^{-6}$ sec. The time lag of the cell in transforming light fluctuations into a fluctuating photocurrent will be appreciable, when the frequency ν of the oscillation to be reproduced becomes so high that a minimum of the photocurrent is affected by the preceding maximum, *i.e.* when

$$\frac{1}{2} \cdot \frac{1}{\nu} \approx 10 \cdot 3.5 \cdot 10^{-6},$$
$$\nu \approx 15\,000 \text{ c/s.}$$

With larger amplification factors N the time lag will become appreciable already at lower frequencies, since a larger value of $\gamma (n-1)$ corresponds to a larger value of N .

By means of a simplified representation we shall now calculate the frequency characteristic of the gas-filled photocell.

Calculation of the frequency characteristic of the gas-filled photocell

If we allow a light fluctuation with the angular frequency ω and a depth of modulation of 100 per cent to fall upon the photocathode the primary photoelectric current i varies according to the following relation:

$$i = i_0 (1 - \cos \omega t) \dots \dots \dots (7)$$

The amplification N which the photocurrent undergoes in the gas can be divided into an inertia-free amplification N_1 by the electrons formed on the path to the anode (as we shall soon see, $N_1 < n$), and a delayed amplification N_2 caused by the ions, which is expressed in the second, third, etc. terms of series (5). Thus for every photoelectron a charge $N_1 e$ is transported without time lag, and in addition a delayed current flows which gradually dies out. It is obvious that the variation of this decaying current may be represented approximately by an exponentially decreasing function of the time:

$$A e^{-q t} \dots \dots \dots (8)$$

where e is the base of the natural logarithms and q must be chosen so that the decrease of (8) with time corresponds to the decrease of the terms of series (5), which succeed each other at intervals of the average ion transit time τ_i ; thus

$$\begin{aligned} e^{-q \tau_i} &= \gamma (n-1), \\ q &= -\frac{\ln \gamma (n-1)}{\tau_i} \dots \dots \dots (9) \end{aligned}$$

The factor A in (8) follows from the condition that the integral of the delayed current from $t = 0$ to $t = \infty$ must be equal to the total charge $N_2 e$ transported with a certain time-lag, thus:

$$\int_0^{\infty} A e^{-q t} dt = N_2 e,$$

from which it follows that

$$A = N_2 e q.$$

N_1 and N_2 are connected by the condition

$$N = N_1 + N_2 \dots \dots \dots (10)$$

The total current I which corresponds to the photocurrent (7) is, according to the above, built up of two parts: the inertia-free part

$$N_1 \cdot i_0 (1 - \cos \omega t)$$

and a part which is found by adding at every moment t the contributions (8) to the current caused during all the preceding time intervals t' , thus

$$\int_{-\infty}^t i_0 (1 - \cos \omega t') N_2 q e^{-q(t-t')} dt'$$

The total current is

$$\begin{aligned} I &= N_1 i_0 (1 - \cos \omega t) + \\ &+ \int_{-\infty}^t i_0 (1 - \cos \omega t') N_2 q e^{-q(t-t')} dt'. \end{aligned}$$

This gives

$$I = N i_0 [1 - \eta \cos (\omega t - \varphi)], \dots \dots (11)$$

with

$$\eta = \frac{1}{N} \sqrt{N_1^2 + \frac{N_2^2 + 2 N_1 N_2}{1 + \omega^2/q^2}} \dots (12)$$

The phase shift φ is of no further interest here⁷⁾. It is, however, important that the alternating current (11) no longer has the depth of modulation of 100 per cent of the primary photocurrent, but only a depth of modulation η , which depends upon the frequency according to (12). From (12) it follows directly that the "efficiency" η of the amplification by ionization is equal to 1 when $\omega = 0$; when $\omega \rightarrow \infty$ it approaches N_1/N . Therefore the part of the amplification which is retained at very high frequencies is N_1/N . If η is plotted as a function of ω , the curve obtained gives the frequency characteristic of the photocell.

N_1 and N_2 must be known in order to calculate η . The inertia-free part, N_1 , of the total amplification is given in the first instance by the previously introduced quantity n , the size of the electron avalanche, the first term of the geometric series (5). Upon closer consideration, however, N_1 is found to be smaller than n . The number of electrons n can be divided into the primary electron and the electrons produced along its path: $n = 1 + (n-1)$. Only the first has its source on the cathode, the others, in each case together with an ion, are produced in the space between cathode and anode. In the movement of each of these electrons toward the anode only the induced charge ze of the electron on the cathode is transported through the external circuit of the cell. The factor z depends upon the point where the electron is produced. For the previously mentioned simple configurations of the electrodes z can easily be calculated. If it is known how the points of origin of the $n-1$ new electrons formed by a primary electron are distributed over the distance between the electrodes, the average value Z of the correction factor can be calculated. The $n-1$ electrons thus cause a non-lagging current $Z(n-1)e$, so that

$$N_1 = 1 + Z(n-1), \dots \dots \dots (13)$$

where $Z < 1$, so that $N_1 < n$.

When all n electrons and all the corresponding ions have reached the anode and cathode respectively, the total charge ne has of course been transported by the current. The part $(1-Z)(n-1)e$, i.e. the induced charge of the ions on the anode, is,

⁷⁾ It would be of interest if the cell were to be used for television. Gas-filled cells are, however, as will be seen later, not suitable for this purpose.

however, transported during the movement of the ions, and must therefore be considered a part of the "delayed" amplification N_2 . By means of (13) N_2 follows from (10).

Under certain simplifying assumptions Z can be calculated, and for a cell with plane electrodes (at $V_a = 100$ volts) Z is found equal to about 0.4. With this value N_1 is calculated from n (or N). η can then be calculated, with N as a parameter. In fig. 4 η is drawn as a function of the frequency for two values of N .

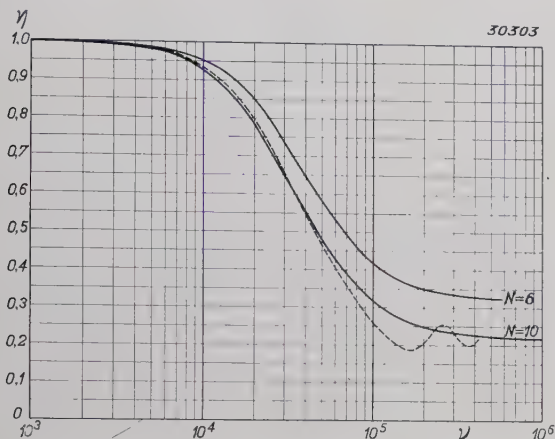


Fig. 4. Theoretically derived frequency characteristics of a gas-filled photocell. The cell is assumed to have plane electrodes with $\gamma = 0.2$. The efficiency η of the amplification is plotted as a function of the frequency ν (in cycles/sec) for two values of the amplification factor N : $N = 6$ and $N = 10$. The dotted curve is calculated according to the more rigorous theory of Ollendorff. For high frequencies the two curves approach the same limiting value: $N_1 = 2.16$ at $N = 10$.

Results and conclusions

The amplification N_1 which remains at very high frequencies (with $Z = 0.4$) is about 1.92 at $n = 3.3$, i.e., in the case where $\gamma = 0.2$, about 32 per cent of the amplification N at low frequencies. At $n = 4$, i.e. $N = 10$, N_1 is about 2.2, or only 22 per cent of N .

The relative decrease in the amplification N_1 at high frequencies thus becomes more pronounced with increasing value of N . The absolute value of N_1 increases somewhat, but approaches a limit of a fundamental nature which can be derived directly from (13). We have seen that n cannot be larger than $1 + 1/\gamma$, since otherwise breakdown occurs in the gas. From this maximum value of n the limiting value of N_1 of $1 + 0.4\gamma$ follows, i.e. 3 when $\gamma = 0.2$.

Due to this limitation of the amplification for high frequencies the advantage of gas-filled photocells over vacuum cells is only slight in the case of television, where frequencies of up to $3 \cdot 10^6$ cycles/sec must be transmitted.

In the region of audio frequencies, as with sound

film, the case is different. In this case satisfactory amplifications, for instance of $N = 10$, can be obtained. As to the shape of the characteristic at the highest frequencies to be reproduced, even a fairly great decrease could be compensated for by a suitable characteristic of the amplifier. In that case, however, the correction would only serve for a single definite curve, i.e. for one value of the amplification factor N . A variation of the anode voltage of the photocell would destroy the compensation. The cells and amplifiers could also no longer be freely interchanged. It is therefore desirable that the cell have a frequency characteristic such that no special adaptation of the amplifier to the photocell is necessary for obtaining a uniform reproduction of all audible frequencies. For this purpose the requirement must be made that the characteristic shall exhibit no larger variations than about 2 dB, which means that η may not decrease by more than about 25 per cent at the highest frequencies to be reproduced. It may be seen from fig. 4 that at $N = 10$, the largest amplification factor ordinarily used, this condition is satisfied: at $\nu < 10,000$ cycles/sec the decrease in η is less than 7 per cent (about 0.6 decibel) which is quite imperceptible with sound film.

The different amplification factors N for which the curves in fig. 4 are drawn are obtained by giving suitable values to the gas pressure in the cell. η is determined by the gas pressure, among other factors (see fig. 2) and therefore also N (see equation (5)). It may be seen from fig. 2 that in general the same value of n may be obtained with two different gas pressures, lying to the right and left of the maximum. With increasing pressure, however, the ion transit time τ_i increases, and with it the time lag of the cell. In order to keep the time lag as small as possible, therefore, the smaller of the two gas pressures corresponding to the desired amplification is chosen.

Exact calculation of the frequency characteristic

For the configuration of electrodes assumed in fig. 4 an exact calculation of η has been given by Ollendorff⁸). In this calculation the geometric series (5) is not replaced by an exponential function. The result is a complicated function of ν , which is drawn in fig. 4 for $N = 10$ and $\gamma = 0.2$ as a dotted line. It is remarkable that the amplification as a function of the frequency exhibits maxima and minima. This phenomenon may be explained as follows. When the average transit time τ_i of the ions is about equal to an odd number of half oscillation times, the excess of ions formed by a maximum of the illumination arrives at the cathode just during one of the following minima of the illumination. This minimum is

⁸) F. Ollendorff, Z. techn. Phys. 13, 606, 1932.

thus filled up somewhat by the electrons freed, which means a decrease in the depth of modulation. Exactly the opposite takes place when τ_i is about equal to a whole number of oscillation times: the ions formed at a light maximum give an extra amplification of one of the following maxima, and thus an increase in the depth of modulation. The theoretically expected maxima and minima in the η curve have actually been found in measurements carried out by Skellett⁹⁾ as a check on the calculations of Ollendorff. The maxima and minima were encountered at the calculated points.

The agreement between the curves according to the exact calculation and those according to our simplified calculation is good as long as $1/\nu$ is several times as large as τ_i . For shorter times the actual variation of the current transported by the ions evidently begins to exert its influence, so that the approximation by an exponential function is no longer adequate. For $\nu \rightarrow \infty$, however, the curve according to the simplified calculation approaches the same limiting value (see (13) as the curve according to Ollendorff.

Measurement of the time lag of photocells

In order to measure the efficiency factor η as a function of the frequency it is necessary to have a light source whose light flux can be modulated sinusoidally with variable frequency. The commonly used method of obtaining such a source by interrupting the light by openings of a suitable form in a rotating disc has the disadvantage that it is difficult to measure at high frequencies. In our measurements, therefore, the modulation of the light was obtained by means of a gas-discharge lamp with light inertia (glow lamp with concentrated discharge in order to obtain sufficiently high surface brightness). The current through the glow lamp was modulated by means of an audio-frequency generator. A disadvantage of this method is that the depth of modulation of the light always remains less than 100 per cent; it decreases especially at higher frequencies. In our case, however, this is no objection since the time lag of the photocell (with not too great intensities of illumination) is practically independent of the depth of modulation of the light. The alternating current component of the photocurrent given by the cell was amplified, and the amplified current was measured by means of a thermocouple and a galvanometer. For checking the amplified photocurrent a cathode ray oscillograph was used with which it was ascertained that the modulation was sinusoidal.

At each frequency the amplification obtained by ionization was determined by measuring the voltage on the resistance R (fig. 1) at an anode voltage $V_a = 100$ volts, and dividing this value by that found at an anode voltage $V_a = 15$ volts. In the latter case no ionization takes place, since V_a

is less than the ionization potential of argon¹⁰⁾, i.e. the amplification is unity. The efficiency factor $\eta(\nu)$ is then obtained by dividing the amplification found by that at very low frequencies (N).

Results of measurements

Measurements on cells of a type used with sound film gave the frequency characteristics reproduced in fig. 5, where η is plotted as a function of the frequency with the amplification factor N as parameter, for the values: $N = 2, 4, 6, 10$ and 15 .

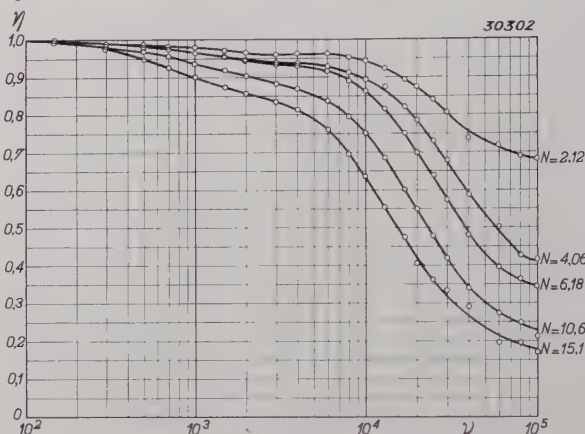


Fig. 5. Experimentally found frequency characteristics $\eta(\nu)$ of a photocell of a type used with sound film, for several values of the amplification factor N .

Although the ionization, which is the cause of the time lag illustrated in fig. 5, depends not only on the gas pressure p , but also on the anode voltage V_a , the variation of $\eta(\nu)$ is found to be independent of p and V_a within certain limits of these quantities, and to be already determined by the amplification factor N in which the influence of p and V_a is combined. For different cells (with the same configuration of the electrodes and the same gas) the same variation of $\eta(\nu)$ is therefore found when V_a is so adjusted with each cell that N has the same value¹¹⁾.

The shape of the curves in fig. 5 corresponds in the main with that of the curves derived theoretically for $N = 10$ and $N = 6$ in fig. 4. The conclusions already drawn from the theoretical curves about the utility of gas-filled cells for different frequencies are therefore confirmed in the main.

¹⁰⁾ In this method of calculation it is assumed that no other sources of inertia are present at the small value of V_a mentioned.

¹¹⁾ The ionization, and with it the time lag, depends further on the light flux on the cell. This influence on the efficiency curve can, however, also be almost entirely removed by reducing the anode voltage V_a so far that N takes on its original value when the light flux is increased. The increasing amplification with larger luminous flux involves a certain amount of non linear distortion. For cells, however, filled with a pure inert gas this distortion is so small, that it is insignificant for sound film purposes.

⁹⁾ A. M. Skellett, J. Appl. Phys. 9, 631, 1938.

More accurate comparison of theory and experiment

In order to test more accurately the theory developed above the measured and the calculated frequency characteristics of a given cell are drawn in *fig. 6* for $N = 10$. The values of τ_i , γ and Z must

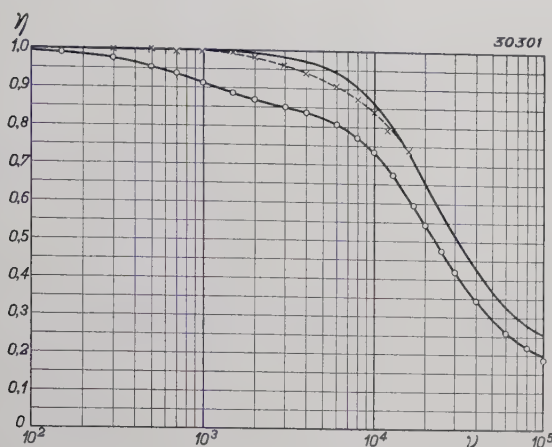


Fig. 6. Comparison of the calculated and measured frequency characteristic (measured points indicated by circles) of a cylindrical cell with rod-shaped anode; $N = 10$, $\gamma = 1/3$. The dotted curve (measured points crosses) is measured with a gas filling of neon plus 10% argon instead of with pure argon.

be known for the calculation. The cell filled with argon at a pressure of 0.07 mm Hg contained a cylindrical cathode 25 mm in diameter, along the axis of which a rod-shaped anode was placed. The average transit time of the ions can be calculated for this case; the value found is $\tau_i = 3.5 \times 10^{-6}$ sec (a value which we have already used above). The coefficient γ of the cathode in this cell was determined experimentally: $\gamma = 1/3$. The factor Z was calculated in the way described above, and at $V_a = 100$ volts it was 0.48.

If the two curves are compared it is seen that the large decrease in the efficiency occurs at the same frequency in both cases. From the measured curve,

however, it follows that the cell has an extra time lag for frequencies between 1 000 and 5 000 cycles/sec. This deviation cannot be explained by a mistake in the value of the constants used for the calculation; the more exact theory of Ollendorff is also unable to reproduce the measured curves. The explanation of the deviation may be found in the occurrence of excited atoms in a metastable state. These metastable atoms, like ions, can free electrons from the cathode, and thus make a contribution to the total amplification. Since, however, they are not charged, and only reach the cathode because of their irregular thermal motion, their transit time is many times longer than the ion transit time. The electrons liberated by metastable atoms will therefore be still much more delayed with respect to the primary photoelectrons than the electrons freed by the ions. This extra late group of electrons will therefore make itself felt already at lower frequencies as a time lag of the amplification. By taking the influence of the metastable atoms into account in the way discussed above in the simplified theory of the time lag, the theoretically calculated curve can be made to correspond entirely with the results found experimentally.

The explanation given is confirmed qualitatively by the following simple test. A cell is filled with neon plus 10 per cent of argon instead of with pure argon. The metastable neon atoms which are formed in this cell will for the most part have returned to the normal state by collisions with argon atoms before they can reach the cathode. It may therefore be expected that the extra time lag at lower frequencies will be considerably smaller in this case than in an ordinary cell filled with argon. The efficiency curve found with this cell actually more nearly resembles the theoretical curve than that of the ordinary cell as may be seen from *fig. 6*.

RECORDING THE CHARACTERISTICS OF TRANSMITTING VALVES

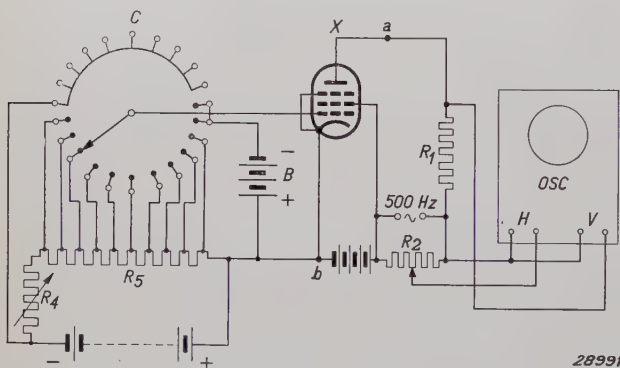
by T.J. DOUMA and P. ZIJLSTRA.

621.317.755:621.396.615.012

A record can be made of the relation between different voltages with a cathode ray tube by applying them to the horizontal and vertical deflection plates respectively. An arrangement is described in this article with which it is possible to record the anode or screen grid current of a transmitting valve as a function of the anode voltage. By this method a number of curves are obtained at one time for different grid voltages.

Introduction

An arrangement was recently discussed in this periodical for recording the characteristics of receiving valves by means of cathode ray tubes. To each set of deflection plates of the cathode ray tube a voltage is applied which is proportional to one of the two quantities whose relation is represented by the characteristic obtained. If, for example, it is desired to record the I_a-V_a characteris-



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Fig. 1. Circuit for recording characteristics of receiving valves. The oscillogram represents the anode current of the valve X as a function of the anode voltage. By means of the rotating switch C a number of different control-grid voltages are applied during every revolution, so that a series of curves appears on the screen.

tic of a valve, the cathode ray is given a horizontal deflection proportional to the anode voltage V_a and a vertical deflection proportional to the anode current I_a . If the anode voltage is then allowed to oscillate with a sufficiently high frequency between zero and its maximum value, a line is observed on the fluorescent screen which has the form of the I_a-V_a curve.

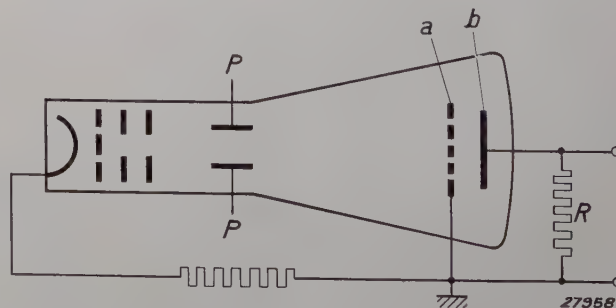
Instead of a single characteristic, it is also possible to make a whole series of characteristics appear on the screen at the same time. In this way it is possible to show the relation between anode current and anode voltage with the control grid voltage as a parameter. To do this it is only necessary that the control grid voltage should take on a number of different values while the characteristic is being recorded.

The advantage of recording characteristics with the oscillograph over the point-by-point measurement with dial instruments lies not only in the great speed, but chiefly in the fact that it is possible to reach parts of the characteristic where slow measurement would lead to overloading of the valve.

These parts of the characteristics may be of great practical importance. This is especially true in the case of valves with which the load in ordinary use is not much smaller than the maximum permissible load, which is often the case with transmitting valves for example. When a transmitting pentode is normally loaded, the maximum permissible continuous value of the grid currents and the anode current is far exceeded at the positive peaks of the oscillating control grid voltage. It is important to know the shape of the characteristic for this high control-grid voltage, in order for instance to be able to calculate the output power of a transmitting valve.

The measurement of transmitting valve characteristics

Fig. 1 gives the principle of the previously described arrangement which was used for the recording of receiving valve characteristics. The anode of the valve to be examined is fed with a direct voltage and an alternating voltage of the same maximum value, so that the total voltage oscil-



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Fig. 2. Diagram of the circuit of the "impulse tube". The electron beam of a cathode ray tube is deflected proportionally to the voltage between the plates P . Whenever this variable voltage passes through certain values, the electron beam falls on a slit in the screen a and part of the electrons pass through to the screen b . A voltage impulse thus occurs on the resistance R .

¹⁾ Philips techn. Rev. 3, 347, 1938.

lates between zero and a maximum value. By means of a rotating commutator C a number of different control grid voltages are successively applied during each revolution, the horizontal deflection is obtained by means of a voltage which is taken from the potentiometer R_2 , and which is proportional to the momentary value of the voltage anode. The vertical deflection is determined by the fall in voltage

sparks occur at the interrupter contacts due to the grid current, so that the voltage cannot be switched off at the desired moments. In the second place the voltage at the interrupter contacts does not remain constant on the occurrence of grid current because the grid circuit has resistance.

It was particularly the second difficulty which led to a modification of the principle. Instead of

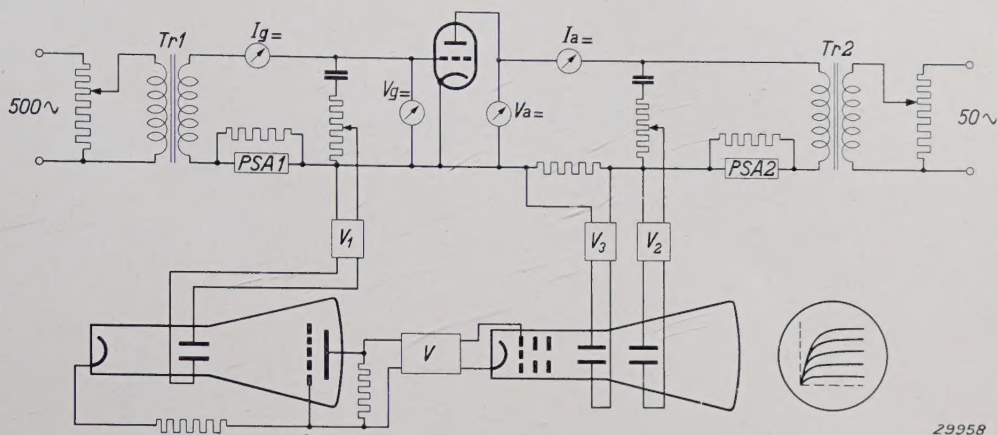


Fig. 3. Diagram of the circuit of the measuring arrangement. V_1 , V_2 , V_3 and V are amplifiers which supply the direct voltage.

at the measuring resistance R_1 , and is proportional to the anode current. On the screen of the tube there appears a series of I_a - V_a characteristics with V_g as a parameter.

This method is useful only when, as in the case given, curves are being recorded with negative control-grid voltages. When the value of the control-grid voltage is positive various difficulties are experienced with the commutator. In the first place

varying the grid voltage in steps, an ordinary practically sinusoidal alternating voltage is supplied to the grid. By means of an electronic switch, which will be described below, it was arranged so that the cathode ray tube only gives light when the grid voltage has just those values which have been chosen as parameters of the I_a - V_a characteristics. In order to carry this out, irrespective of the form of the grid alternating voltage, which may change in some cases due to the appearance of grid currents, a switch arrangement without inertia is required. This can be obtained with the help of a second cathode ray tube which will be called the impuletube²⁾.

Fig. 2 indicates the principle of the impulse tube. The tube contains a pair of deflection plates P , to which is applied a voltage proportional to the control-grid voltage of the tube being investigated. Instead of a screen the impulse tube has two parallel plates a and b , the first of which is provided with thirty narrow parallel slits at equal distances. When the cathode ray swings back and forth across plate a under the influence of an oscillating deflection voltage, a small current strikes the plate b every time the ray passes across a slit, and a voltage impulse on the resistance R results. After amplification this impulse with the correct sign is applied to the regulatory electrode of the cathode ray tube

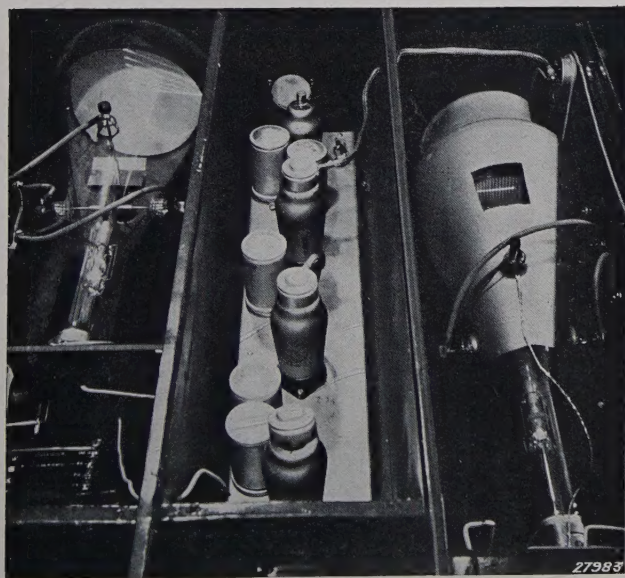


Fig. 4. Photograph of the measuring apparatus. On the left the characteristic tube, on the right the impulse tube.

²⁾ This idea was proposed by K. Posthumus.

which records the characteristics, and which we shall call the "characteristic tube" to avoid misunderstanding. This regulatory electrode has a

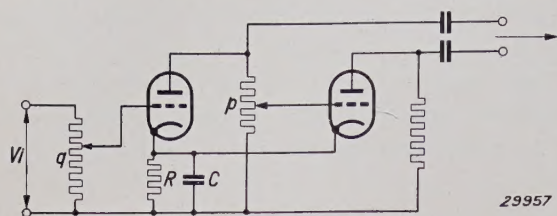


Fig. 5. Diagram of the circuit of the amplifiers V_1 , V_2 , V_3 . With a given input voltage, phase and amplitude of the output voltage may be regulated by means of the potentiometers p and q .

negative bias such that the signal current of the characteristic tube is usually completely suppressed, and only flows during the impulses.

the transformer $Tr 1$, while the anode of the valve is supplied through $Tr 2$ with an alternating voltage of 50 cycles/sec. Both voltages can be regulated and read. In addition the grid as well as the anode has a direct current which can also be regulated and read.

The grid direct voltage is best chosen strongly negative, so that current only flows during a small part of the period. This greatly reduces the average load³⁾. The amplitude of the grid alternating voltage must of course be chosen so great that the maximum grid voltage still has the desired value. The anode direct voltage, as mentioned before, is best adjusted at a value equal to the amplitude of the anode alternating voltage.

The measuring voltages taken off are fed to the amplifiers V_1 , V_2 and V_3 . V_1 receives the control-

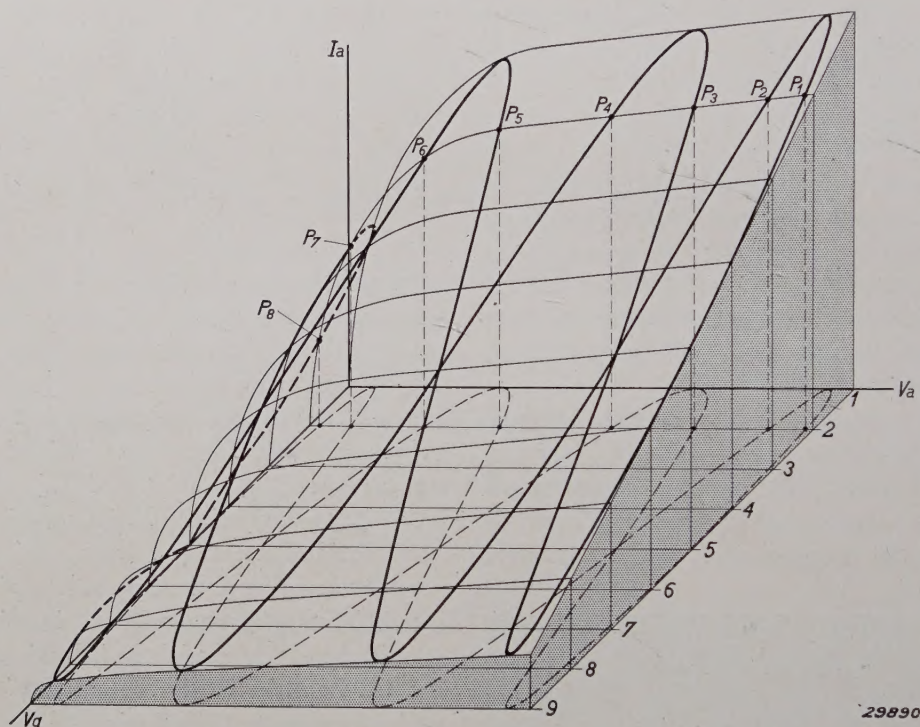


Fig. 6. Anode current I_a as a function of the anode voltage V_a and the control-grid voltage V_g . The electron beam in the impulse tube in the case shown passes nine slits at grid voltages indicated by 1-9. The relation between the grid voltage and the anode voltage during measurement is given by the dotted Lissajous figure in the V_a - V_g plane. The points $P_1 \dots P_9$ are given as examples of the points which appear on the screen of the characteristic tube due to the second slit of the impulse tube. These points are actually not stationary but run along one of the I_a - V_a curves. In the same way eight other I_a - V_a curves are drawn in this case.

Details of the circuit

After this description of the impulse tube we shall consider briefly the other components of the measuring arrangement. The diagram of the circuit of the measuring arrangement is reproduced in fig. 3, while fig. 4 is a photograph of it. An alternating voltage of 500 cycles/sec is supplied to the control grid of the valve to be investigated by

grid voltage, V_2 the anode voltage and V_3 the anode current. The amplified control-grid voltage is fed to the impulse tube and finally regulates the beam current of the characteristic tube. The anode voltage

³⁾ This adjustment of grid direct voltage and alternating voltage, the so-called class C amplification, is often applied in practice to transmitting valves. See in this connection the article on transmitting pentodes: Philips techn. Rev. 2, 257, 1937.

provides the horizontal deflection and the anode current the vertical deflection of the electron beam. In order to obtain a good picture of the characteristics it is necessary that the amplified voltages on the deflection plates and the regulatory electrode of the characteristic tube should be exactly in phase with the corresponding quantities on grid or anode of the transmitting valve. A certain difference of time between the voltage on the characteristic tube and the corresponding quantity on the transmitting tube is of course permissible if it is the same for all three quantities. The amplifiers are so changed that the phase relation of output voltage and input voltage can be regulated to a certain extent. In the ordinary adjustment output and input voltage are in phase. If, however, for instance due to coupling condensers, a phase shift occurs, it must be corrected by a slight change of adjustment.

The circuit diagram of the amplifiers is given in *fig. 5*. Part of the input voltage V_i is tapped off from the potentiometer q and is amplified in two stages of resistance amplification. Each of the two anodes is connected over a condenser with one of the deflection plates of the cathode ray tube.

As may be seen the sum of the two anode currents flows through the circuit formed by the resistance R and the condenser C . This causes a feedback. The feedback voltage will not be in phase with the input voltage because the RC circuit does not have a purely ohmic impedance. The result is that the output voltage is generally also out of phase with the input voltage. If, however, the anode alternating currents of the two amplifier valves have precisely opposite amplitudes, so that the sum of the anode currents is constant, the back coupling disappears and with it the phase difference between output voltage and input voltage. This latter is the normal adjustment.

As may be seen from the diagram the normal adjustment can be obtained by setting potentiometer p so that the amplitudes of the two anode currents become equal in size. Since the two amplifier valves work in opposite phases, the sum of the two anode currents then really does remain constant and the phase shift becomes zero. When, however, a slight phase shift occurs in the external circuits of the amplifier, it can be corrected by changing the potentiometer p .

How the installation works

The way in which the images are formed can be seen from *fig. 6*. In that figure of the curved surface $I_a = f(V_a, V_g)$ is drawn with the I_a-V_a

characteristics corresponding to nine aequidistant values of the grid voltage. Each of these voltages may be made to correspond to a slit in the plate of the impulse tube; when the electron beam passes one of these slits the grid voltage has a definite value and a point of the respective I_a-V_a characteristic is drawn, point P for example. On the screen of the characteristic tube appear the projections on the I_a-V_a plane of the nine characteristics drawn on the surface.

For the sake of clearness in *fig. 6* the frequency of the grid voltage is taken equal to four times that of the anode voltage (instead of ten times), and both are considered to be sinusoidal. It may be seen that the same points are traced over and over, so that a stationary picture of discrete points is obtained. In the V_a-V_g plane the same curve is traced over and over, namely a Lissajous figure for the frequency ratio 4 : 1.

The direct voltage for the anode, as already indicated, is chosen so that the total anode voltage varies between zero and twice the value of the direct voltage. It is hereby assumed that the anode current causes practically no voltage loss in the external circuit of the anode, a circumstance which is not always attainable in practice. If this is not the case the parts of the I_a-V_a characteristic corresponding to the highest positive grid anode voltages are of course not reached (see *fig. 7*).

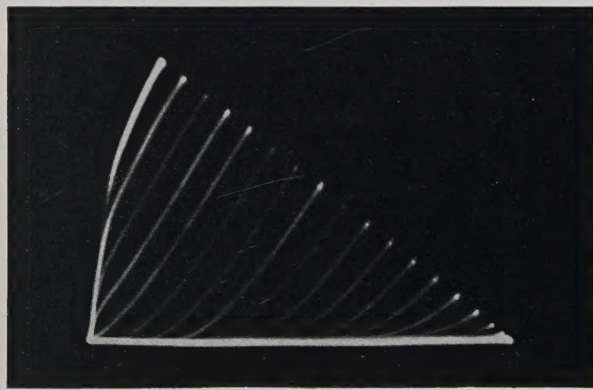


Fig. 7. I_a-V_a characteristics of the transmitter triode TC⁰³/₃. Abscissa : 1 cm = 150 volts; ordinate: 1 cm = 30 mA. The anode current was limited by an external resistance. The uppermost curve is for $V_g = 40$ volts, in the succeeding curves the grid voltage is 10 volts lower in every case.

If the frequencies of the alternating voltages for grid and anode of the valve being investigated were 500 and 50 cycles/sec respectively, a stationary image, as is *fig. 6*, consisting of a number of points would appear. Actually the two voltages are taken from two independent sources which are practically never exactly synchronous. The result is that the points are not stationary but run along the char-

acteristic, so that the curves are drawn as continuous lines.

In order to obtain sufficiently sharp points on the characteristic tube, the width of the slits and the diameter of the electron beam must be carefully chosen in the construction of the impulse tube. If the width of slit or diameter of beam is too great, vertical lines instead of points appear in the characteristic tube, which decreases the precision. If they are both too small the impulses are too short, and the brightness of the image in the characteristic tube is too low.

Furthermore, in order to obtain sharp charac-

teristics it is necessary that the impulse amplifier also be able to amplify relatively high frequencies sufficiently, so that the correct form of the voltage peaks will be retained. If for example twenty slits have been passed over, and the frequency of the grid voltage is 500 cycles/sec, then, since each slit is passed over twice in every oscillation, there will be $500 \cdot 20 \cdot 2 = 20\,000$ impulses per sec. The duration of each voltage peak is thus in any case small compared with $1/20\,000$ sec, and the amplifier must be able to amplify high harmonics of 20 000 cycles/sec in order to transmit these voltage peaks undistorted.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF THE N.V. PHILIPS GLOEILAMPENFABRIEKN

1335: F. M. Penning: The relation between the Paschen breakdown curve and the elementary processes (Ned. T. Natuurk. **5**, 146-151, June 1938).

For several typical cases (air, Ne, Ne + 0.1% Ar) the relation is given between the breakdown potential between parallel plates and the elementary processes. From the manner in which the breakdown potential depends upon the potential difference traversed per free path, the relation is deduced between the breakdown potential and the product of gas density and breakdown distance (Paschen curve), which is a measure of the breakdown distance with unit density of gas. The shapes of these different kinds of curves are discussed.

1336: M. J. Druyvesteyn: Various kinds of breakdown in a gas. Ned. T. Natuurk. **5**, 85-95, Apr. 1938).

The breakdown in a gas differs in many cases from the simple case of breakdown between two parallel plates. The breakdown potential and the characteristic of the corona discharge are explained qualitatively. The ignition of the positive column and of an arc with externally heated cathode are discussed.

1337: W. de Groot: Electrical breakdown in gases as a phenomenon of finite duration (Ned. T. Natuurk. **5**, 152-167, June 1938).

The experiments of Strigel, Braunbek, Hertz and Schade on the temporal aspect of the breakdown in gases at different pressures are discussed. Especially attention is given to Schonland's physical explanation of lighting discharges, and the possibility is pointed out of generating artificial lighting.

1338: Balth. van der Pol and H. Bremmer: The propagation of radio waves over a finitely conducting spherical earth (Phil. Mag. **25**, 817-834, Suppl. June 1938).

As a supplement to previous investigations (cf. 1264 and also 1318) the distribution of field strength is calculated for a transmitter which emits radio waves over a homogeneous spherical earth with an arbitrary electrical conductivity and dielectric constant. The transmitter and receiver are assumed to be on the surface of the earth. As far as is known to the authors the calculations give the most accurate results. Finally curves are given for the field strength as a function of the distance of propagation over the sea and over an average type of land.
